Prepared for:

Autoridad del Canal de Panamá

Salt Water Intrusion Analysis
Panama Canal Locks

Future situation: Post-Panamax Locks

Report B: single-lift locks
Report C: three-lift locks
Report D: two-lift locks

September 2003

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September 2003

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CLIENT:	Autoridad del Canal de Panamá (ACP)
TITLE:	Salt Water Intrusion Analysis Panama Canal Locks. Future situation: Post-Panamax Locks

ABSTRACT:

Autoridad del Canal de Panamá (ACP) has awarded WL | Delft Hydraulics the contract for 'Salt Water Intrusion Analysis for the Existing and Proposed Post-Panamax Locks at the Panama Canal' (contract SAA-74337). The objectives of the services of WL | Delft Hydraulics were to analyse the salt water intrusion for the existing and proposed Post-Panamax locks and to develop the required tools. To that purpose the services included:

- review of present canal operation and data on salt water intrusion in the existing situation
- collection of field data on salt water intrusion, both in the wet and dry season
- numerical modelling, validation and analysis of salt water intrusion for the existing situation
- numerical modelling and analysis of salt water intrusion for three configurations of proposed Post-Panamax locks
- development of specifications for further testing of salt water intrusion using physical scale models of the proposed locks and water saving basins

The present report presents the results of the salt water intrusion analysis for the future situation with new, third shipping lane and Post-Panamax locks. The first part of the report describes and compares the salt water intrusion for three configurations of Post-Panamax locks. The next three parts of the report, indicated as Report B, Report C and Report D, present the numerical model and the results of salt water intrusion simulations for each of these three configurations of Post-Panamax locks separately. These reports can be read independently; each of them contains full information on the numerical simulation model for the specific lock configuration.
Report A, dated June 2003, presents the results of the salt water intrusion analysis for the existing situation, including a review of the present canal operation, a review of available data on salt water intrusion in the existing situation, the collection of field data on salinity levels in the canal area in wet and dry season, the development of the numerical simulation model, and the analysis of salt water intrusion in the existing situation. It contains also specifications for further testing of salt water intrusion through the locks on the canal using physical scale models.

REFERENCES: FMCC -Contract no SAA-74337, signed by ACP on 9 October 2001
Notice to proceed, ACP, dated 18 October 2001

VER.	ORIGINATOR		DATE	REMARKS	REVIEW		APPROVED BY	
01	T.H.G. Jongeling		June 2003		F.C. van der Knaap			
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Salt Water Intrusion Analysis Panama Canal Locks
Future Situation: Post-Panamax Locks

Contents

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I 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 consequently 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 'Saltwater Intrusion Analysis for the Existing and Proposed Post-Panamax Locks at the Panama Canal' (contract SAA-74337). The formal Notice to Proceed, dated 18 October 2001, was received by fax on 19 October 2001.
The objectives of the services of WL | Delft Hydraulics were to analyse the salt water intrusion for the existing and proposed Post-Panamax locks and to develop the required tools. To that purpose the services included:

- review of present canal operation and data on salt water intrusion in the existing situation
- collection of field data on salt water intrusion, both in the wet and dry season

- numerical modelling, validation and analysis of salt water intrusion for the existing situation
- numerical modelling and analysis of salt water intrusion for three-lift and single-lift configurations of proposed Post-Panamax locks

In addition, the services included:

- development of specifications for further testing of salt water intrusion using physical scale models of the proposed locks and water saving basins

The contract was extended January 2003; the objective of this extension was:

- numerical modelling and analysis of salt water intrusion for two-lift configuration of proposed Post-Panamax locks

The present report presents the results of the salt water intrusion analysis for the future situation with new, third shipping lane and Post-Panamax locks. The first part of the report describes and compares the salt water intrusion for the three configurations of Post-Panamax locks, that was studied under the present contract. Comments of ACP to earlier draft reports, mainly on the set up of the salt water intrusion simulation model and the use of salt exchange coefficients in this model, are treated here and further explained. The next three parts of the report, indicated as Report B, Report C and Report D, present the numerical model and the results of salt water intrusion simulations for each of these three configurations of Post-Panamax locks separately. These reports can be read independently; each of them contains full information on the numerical simulation model for the specific lock configuration.

Report A, dated June 2003, presents the results of the salt water intrusion analysis for the existing situation, including a review of the present canal operation, a review of available data on salt intrusion in the existing situation, the collection of field data on salinity levels in the canal area in wet and dry season, the development of the numerical simulation model, and the analysis of salt water intrusion in the existing situation. It contains also specifications for further testing of salt water intrusion through the locks on the canal using physical scale models.

2 Salt water intrusion Post-Panamax Locks

In this chapter we present a comparison of 1-lift, 2-lift and 3-lift lock configurations of Post-Panamax Locks on the subject of salt water intrusion and fresh water needs. The numerical model that was developed to simulate the salt water intrusion, is explained in Reports B, C and D for each of the lock configurations. However, we have noticed from comments of ACP at draft reports, that the set up of the model and, in particular, the function of forebays and tailbays requires some more explanation. Also the use of salt exchange coefficients and the selected values of exchange coefficients require more explanation. We therefore start with a discussion on modelling aspects of the salt water intrusion simulation model and will than continu with a comparison of results for 1-lift, 2-lift and 3-lift locks, also in relation to the existing situation.

2.1 Simulation model for salt water intrusion

2.1.1 Purpose of the simulation model

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

The simulation model is not aimed, and also not capable, to predict the time dependent dissemination of salt water in Miraflores Lake, Gaillard Cut and Gatun Lake. To that purpose a full three-dimensional (3d) flow model is required, that is also capable to compute the flows driven by density-differences. The salt water load caused by the operation of existing and Post-Panamax Locks and computed in the present study, may serve as input for such a 3d-model. Other input needed in the 3d-flow computation concerns the inflow of fresh water from rivers which discharge into the lakes (including direct effects of rainfall in the lakes and evaporation), the outflow of water through Gatun power station and spillway, Miraflores cooling water offtake and spillway, drinking water pumping stations, and locks on the existing and new shipping lanes. The 3d-model requires the modelling of the bathymetry of the lakes and Gaillard Cut. The effects of the sailing ships (caused by screw race and return currents, in particular in Gaillard Cut) and wind should be taken into account.
The computations with the 3d-model should be done for a long period of time, taking into account the seasonal variations of lake water levels and water spillages, time dependent salt water loads and developments in ship traffic intensities. It requires huge modelling and computational efforts. However, further schematized 3d flow computations are possible, for example for Gaillard Cut only, to get an impression of possible salinity levels in the neigh-

bourhood of the drinking water inlet near Paraiso. These computations can be done taking the salt water loads computed with the salt water intrusion simulation model, as input. ACP is advised to consider the execution of 3d density flow computations after a configuration of Post-Panamax Locks has been selected for a further development and design.

2.1.2 Design of the simulation model and function of forebays and tailbays

Essentially, the simulation model consists of a number of separate basins (lock chambers, water saving basins, forebays and tailbays of locks, lakes and sea entrances), 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 salt concentration (the quantity of dissolved salts in ppt) of a basin is defined in the simulation model as a volume-averaged salt concentration. The salt content of a basin can thus be computed as the product of water volume and concentration. In reality the salt concentration varies in vertical and horizontal direction; salt layers and internal waves occur near the bottom of basins, but in lock chambers salt water layers are also mixed up with the upper water body during filling. Many other factors influence the actual, time dependent distribution of salt in the various basins.
The process of salt water intrusion through the locks can only partly, in a schematized way for single steps of the lockage process, be modelled with a 3d-flow model. These computations help to understand the hydraulic processes and provide also a quantitative estimate of the salt exchange between basins in the various steps of the lockage process. To that purpose we have used our Delft3D flow model.
The use of a 3d model for the study of salt water intrusion is also not possible in view of the long computation times; the run time on a fast PC is already several hours for only one step of the lockage process in a schematized model. When changes in salinity levels during a long period of time (up to 50 years) are considered, 3d modelling is fully out of the question.
Instead we have built a simulation model that computes the exchange of water and salt between basins in the successive steps of the lockage process with the help of mass balance and salt balance equations for the water volumes of the considered adjacent basins. Salt exchange coefficients (dimensionless) are used in the salt balance equations to quanitify the salt exchange. It will be clear that these salt exchange coefficients have to be selected with care and must be representative for the salt exchange phenomena in a specific step of the lockage process. The salt balance equations describe the exchange of salt between two mutually connected basins in the phase that water levels are equalized (step I) and in the phase that gates between the basins are open and water is exchanged because of the ship movement and density differences (step II).

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 for 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.

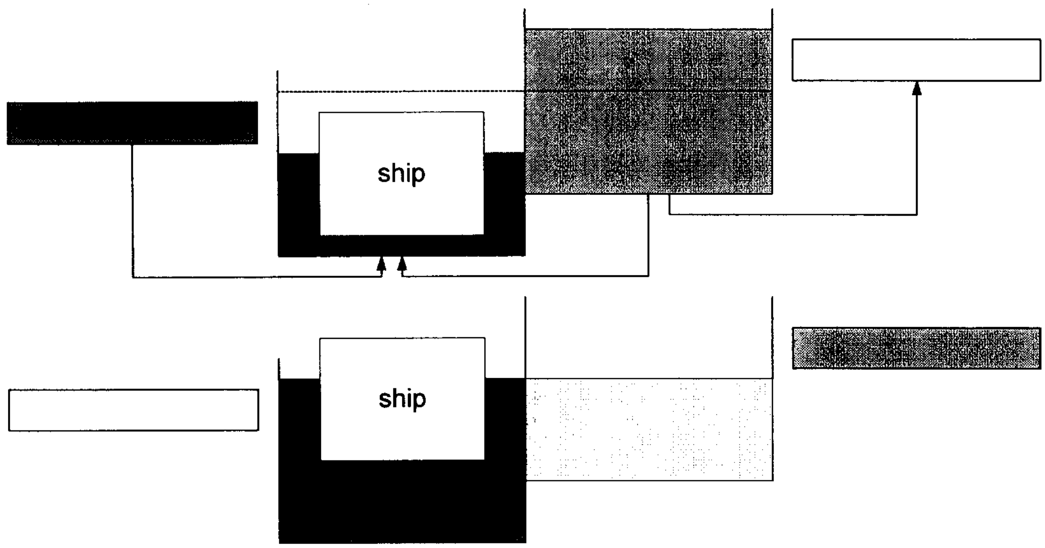
2.1.3 Salt exchange coefficients

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 steps. Two basic steps are distinguished in the lockage process:

- Step I: the water level in two adjacent basins is 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 and density flows develop.

These two basic steps repeat each time that a ship moves from one basin to another. 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 (see hereafter). The products $e_x.V_{ref}.c$ (c = salt concentration), $e_x.V_{save}.c$ and $e_x.S.c$ all represent a certain quantity of salt in the salt balance.

The salt balance equations in step I of the uplockage process are of the general form (wsb's included):



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

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

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

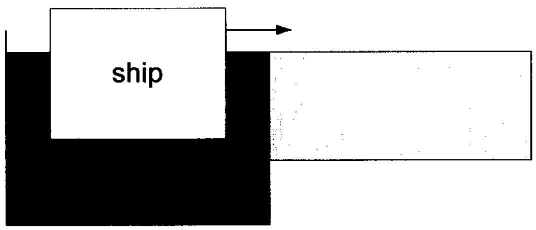
$$c_{wsbhigh2} = \frac{(V_{wsbhigh1} \cdot c_{wsbhigh1}) + (e_{wsbfill} \cdot V_{save} \cdot c_{high1})}{V_{wsbhigh2}}$$

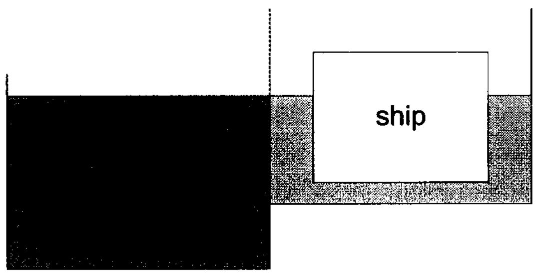
Note: subscript *high* refers to the higher basin, subscrift *low* to the lower basin, subscript *wsbhigh* to the wsb 's of the higher basin, subscript *wsblow* to the wsb's of the lower basin, subscript *1* refers to the beginning of the step, subscript *2* refers to the end of the step.

Equal 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 and $e_{wsbfill}$ 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 and $e_{wsbfill}$ 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, and D for further explanations). The exchange coefficient $e_{wsbempty}$ is always set to 1 in the present study. We assume that the water in the wsb's 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 prior to the withdrawal.

The following set of equations (in general form) is applied in step II of the uplockage process:





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

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

Equations for step II of the downlockage process are similar, apart from the last right-hand term. This term in the downlockage equations contains the initial salt concentration c_{low1} of the lower basin (instead of c_{high1} of the higher basin) and has a different sign.

The equations show that the density driven exchange of salt water between the two basins is defined in the simulation model as the product of an exchange coefficient e_x, the water volume V_{ref} of the higher basin (no ship in the higher basin) and the initial salt concentration difference between the two basins. The exchange coefficient e_x can either by positive, nill or negative. In the case of a positive value salt water is transferred from lower basin to higher basin, provided that the initial salt concentration difference between lower basin and higher basin is positive.
The equations show also that a water quantity (containing salt) equal to the volume S of the ship is transferred in a direction opposite to the ship movement (third, right-hand term). The second right-hand term is in fact a balance term: it quantifies the additional salt exchange after the ship's volume has been exchanged. It will be clear that the exchange coefficient e_x

must be representative for the salt water exchange that occurs in a complex hydraulic process, in which in particular the density differences, the dimensions and draught of the ship, the gate opening time, and the propellor action are influencing factors.

When we put:

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

where e_{x0} = value of e_x for S = 0, the salt balance equations change in:

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) - e_{x0} \cdot (V_{ref} - S) . (c_{low1} - c_{high1}) + (S . c_{high1})}{V_{low2}}$$

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) + e_{x0} \cdot (V_{ref} - S) . (c_{low1} - c_{high1}) - (S . c_{high1})}{V_{high2}}$$

These equations are used in the simulation model; the value of e_{x0} is read from an input table. The exchange coefficient e_{x0} can be positive or negative. The values of e_{x0} have been 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, and D for further explanations). All selected values are positive and smaller than 1, and in most cases smaller than 0.2.

The general salt balance equations discussed above are also applicable to the combination of tailbay and lock chamber and the combination of lock chamber and forebay.
As described earlier the exchange of salt water between forebay (or tailbay) and lake is executed at the moment that a 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. If relevant, the exchange of salt water is also evoked when turn around lock operations are executed. 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.
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.

Next tables present an overview of the exchange coefficients, which have been selected for the various lock configurations.

Low basin	*High basin*	*Exchange coefficients existing locks, Pacific side*		*Exchange coefficients existing locks, Atlantic side*	
		Uplockage	*Downlockage*	*Uplockage*	*Downlockage*
Tailbay sea	Lower Lock	1.3	1.2	1.3	1.2
Lower Lock	Middle Lock	1.3	1.2	1.3	1.2
Middle Lock	Forebay ML	0.95	0.85	//////////////////	//////////////////
Tailbay ML	Upper Lock	1.3	1.2	//////////////////	//////////////////
Middle Lock	Upper Lock	//////////////////	//////////////////	1.3	1.2
Upper Lock	Forebay GL	0.95	0.85	0.95	0.85

Table 2.1 Existing Locks, exchange coefficients step I (equalize water levels)

The 'uplockage coefficients' in step I are somewhat greater than the 'downlockage coefficients'. This choice is related to the differences which exist in the equalizing step for an uplocking ship and a downlocking ship (the position of the ship plays a role).

Low basin	*High basin*	*Exchange coefficients existing locks, Pacific side*		*Exchange coefficients existing locks, Atlantic side*	
		Uplockage	*Downlockage*	*Uplockage*	*Downlockage*
Tailbay sea	Lower Lock	0.9	0.4	0.7	0.4
Lower Lock	Middle Lock	0.05	0.15	0.05	0.15
Middle Lock	Forebay ML	0.0	0.1	//////////////////	//////////////////
Tailbay ML	Upper Lock	0.05	0.1	//////////////////	//////////////////
Middle Lock	Upper Lock	//////////////////	//////////////////	0.0	0.1
Upper Lock	Forebay GL	0.0	0.05	0.0	0.05

Table 2.2 Existing Locks, exchange coefficients step II (move ship)

Note that the exchange coefficients for the adjacent basins 'tailbay sea – lower lock' in step II are higher at uplockage than at downlockage. The reason for this choice is that the gates of the lower locks are opened far before the uplocking ship enters the lower lock, thus enabling density flows to fully develop. In the case of downlockage the gates of the lower locks are closed immediately after exit of the ship, causing a lesser exchange of salt water. In general however, a downlocking ship causes a stronger inflow of salt water than an uplocking ship. This effect is included in the choice of the exchange coefficients: the 'downlockage coefficients' in step II are generally greater than the 'uplockage coefficients'.

Low basin	*High basin*	*Exchange cefficients 3-lift locks with wsb's*						*Exchange cefficients 3-lift locks without wsb's*	
		Uplockage			*Downlockage*			*Uplockage*	*Downlockage*
		fill wsb	*empty wsb*	*equalize*	*fill wsb*	*empty wsb*	*equalize*	*equalize*	*equalize*
Tailbay sea	Lower Lock	1.35	/////	1.25	1.2	/////	1.2	1.3	1.2
Lower Lock	Middle Lock	1.35	1.0	1.25	1.2	1.0	1.2	1.3	1.2
Middle Lock	Upper Lock	1.35	1.0	1.25	1.2	1.0	1.2	1.3	1.2
Upper Lock	Forebay GL	/////	1.0	0.95	/////	1.0	0.85	0.95	0.85

Table 2.3 Three-lift Post Panamax Locks, exchange coefficients step I (fill wsb's, empty wsb's, equalize water levels)

Low basin	*High basin*	*Exchange cefficients 3-lift locks with and without wsb's*	
		Uplockage	*Downlockage*
Tailbay sea	Lower Lock	0.7	0.4
Lower Lock	Middle Lock	0.05	0.15
Middle Lock	Forebay ML	0.0	0.1
Upper Lock	Forebay GL	0.0	0.05

Table 2.4 Three-lift Post Panamax Locks, exchange coefficients step II (move ship)

Low basin	*High basin*	*Exchange cefficients 2-lift locks with wsb's*						*Exchange cefficients 2-lift locks without wsb's*	
		Uplockage			*Downlockage*			*Uplockage*	*Downlockage*
		fill wsb	*empty wsb*	*equalize*	*fill wsb*	*empty wsb*	*equalize*	*equalize*	*equalize*
Tailbay sea	Lower Lock	1.3	/////	1.15	1.15	/////	1.15	1.25	1.15
Lower Lock	Upper Lock	1.3	1.0	1.15	1.15	1.0	1.15	1.25	1.15
Upper Lock	Forebay GL	/////	1.0	0.95	/////	1.0	0.85	0.95	0.85

Table 2.5 Two-lift Post Panamax Locks, exchange coefficients step I (fill wsb's, empty wsb's, equalize water levels)

Low basin	*High basin*	*Exchange cefficients 2-lift locks with and without wsb's*	
		Uplockage	*Downlockage*
Tailbay sea	Lower Lock	0.7	0.4
Lower Lock	Upper Lock	0.05	0.15
Upper Lock	Forebay GL	0.0	0.1

Table 2.6 Two-lift Post Panamax Locks, exchange coefficients step II (move ship)

Low basin	*High basin*	*Exchange cefficients 1-lift locks with wsb's*						*Exchange cefficients 1-lift locks without wsb's*	
		Uplockage			*Downlockage*			*Uplockage*	*Downlockage*
		fill wsb	*empty wsb*	*equalize*	*fill wsb*	*empty wsb*	*equalize*	*equalize*	*equalize*
Tailbay sea	Lock	1.25	/////	1.05	1.1	/////	1.1	1.2	1.1
Lock	Forebay GL	/////	1.0	0.95	/////	1.0	0.85	0.95	0.85

Table 2.7 Single-lift Post Panamax Locks, exchange coefficients step I (fill wsb's, empty wsb's, equalize water levels)

Low basin	*High basin*	*Exchange cefficients 1-lift locks with and without wsb's*	
		Uplockage	*Downlockage*
Tailbay sea	Lock	0.7	0.4
Lock	Forebay GL	0.05	0.15

Table 2.8 Single-lift Post Panamax Locks, exchange coefficients step II (move ship)

The selected exchange coefficients for steps I and II of the uplockage and downlockage process form a consistent set of values, both for the existing locks and the Post-Panamax locks at the Pacific and Atlantic side.

2.1.4 Spillage of salt water from the lakes

The set of exchange coefficients for the existing locks was validated on the basis of site measurements executed in wet and dry season in locks and lakes (see Report A for reference). These measurements showed that the salt concentration of Miraflores Lake varies in dependence of dry and wet season; the overall (volume averaged) salinity was about 0.7 ppt in the wet season and 1.5 ppt in the dry season (period November 2001 – April 2002). The salinity level of Gatun Lake appeared very low; salinity values were smaller than 0.1 ppt. More accurate salinity measurements were not possible with the applied CTD sensors, which have a lower measurement limit of about 0.1 ppt. In the forebays of the Gatun Locks salinity levels up to 0.2 ppt were measured near the bed during downlockage of ships.

The varying salinity levels of Miraflores Lake and Gatun Lake were used in the validation to check the set of exchange coefficients. Measurements in the locks and results of Delft3D computations were used to select values for individual exchange coefficients.

Another factor in the validation was the release of water at Gatun Dam (through spillway and power station) and Miraflores Dam (through spillway and cooling water offtake). These water releases are also the cause of a partial outflow of salt water.
Daily water releases are prescribed in the numerical simulation through an input table. The effect of water releases on the salt concentration of the lake is computed with the help of next salt balance equation:

$$c_{lake2} = \frac{(V_{lake1} \cdot c_{lake1}) - (e_x \cdot Q \cdot c_{lake1})}{V_{lake2}}$$

where

e_x = exchange coefficient (-); no outflow of salt water when $e_x = 0$
Q = outflow discharge (m^3/s)
V_{lake} = water volume of lake (m^3)

The equation is such defined that when a value 1 is selected for the exchange coefficient the salt concentration of the spilled water is the same as the volume averaged salt concentration of the lake. The choice of $e_x = 1$ is, however, not realistic. In Miraflores Lake a short-cut flow is likely between Miraflores Locks and the water outlets at Miraflores Dam; this flow may be sustained by the overall flow pattern in the lake, that causes a net water transport in southern direction (the outlets in Miraflores Dam and Miraflores Locks draw water from the lake). Though higher salt concentrations have been measured near the bed of the deeper shipping channel towards Pedro Miguel Locks indicating the existence of a density flow away from Miraflores Locks, it is reasonable to assume that the intruded salt water will not disseminate over the full lake volume, but has some preference to partly remain in the southern area of the lake. The salt concentration of the spilled water will thus generally be higher than the average salt concentration of the full lake.
The water volume of Gatun Lake is about 220 times greater than the water volume of Miraflores Lake. The prevailing flow direction is towards the northern area near Gatun Dam and Gatun Locks, in particular in the wet season when large quantities of water are spilled. Salt water may intrude through Pedro Miguel Locks and Gaillard Cut in the south and Gatun Locks in the north. As will be discussed hereafter most salt water enters Gatun Lake through Gatun Locks. It is most likely that the intruded salt water propagates along the bed of the deeper shipping channel and follows the deeper parts (old Chagres River) towards the outlets in Gatun Dam. The present salt concentration levels in Gatun Lake are very low and below 0.1 ppt (= lower limit of CTD sensors used during our site surveys), also in the area near Gatun Dam. Though despite we could not measure different salinity values, we expect that the salt concentration in the area near Gatun Dam is higher than the average salt concentration of the full lake.
The expected concentration of more saline water in the areas near the outlets at Gatun Dam and Miraflores Dam is tested in validation runs. In final validation runs we have used next exchange coefficients for water releases at Gatun Dam and Miraflores Dam:

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

Table 2.9 Exchange coefficients outlets

These coefficients together with the coherent set of lock exchange coefficients for Atlantic locks and Pacific locks appeared to predict volume-averaged salt concentration levels in

Miraflores Lake and seasonal variations as were measured in wet and dry season; a very low volume-averaged salt concentration level was predicted for Gatun Lake, similar as in the existing situation. See also Report A for a further explanation.

Equal exchange coefficients have been applied in numerical simulations for the future situation with Post-Panamax Locks (all variants). We decided to do so for next reasons:

- Most probably, the overall flow patterns in Miraflores Lake and water releases from the lake will not importantly change. We expect therefore that the tendency remains that a part of the intruded salt water concentrates in the southern area.
- The resultant flows in Gatun Lake will still be in northern direction towards the area near Gatun Dam and Gatun Locks. Though the distribution of outflow discharge of Gatun Dam and Gatun Locks will be different (also depending on the quantity of water that is supplied to the lake), the salt water that intrudes through the Atlantic locks will still have preference to remain in the deeper northern areas of the lake. The extra salt water that intrudes through the Pacific locks may proceed in northern direction along the deeper shipping channel, but this is uncertain.
- A better founded choice of exchange-coefficient values (both for the existing situation and the future situation) can only be made after extensive 3d-flow computations; if such computations are possible it requires huge modelling and computational efforts (see Section 2.1.1).
- When equal exchange coefficients are applied for the existing situation and the future situation a more straight forward comparison is possible of the effects of the various designs of Post-Panamax Locks and different water supply scenarios.

In next sections we will discuss and compare the computed salt water intrusion in the existing and future situation.

2.2 Salt water intrusion existing situation

The salinity levels of the lakes in the existing situation form a basis for a comparison with salinity levels in the future situation with Post-Panamax Locks. The comparison will be for year 50 after opening of the new shipping lane. We have executed salt-water intrusion simulation runs for the situation that Post-Panamax Locks are in operation (together with the existing locks) and the situation that the Post-Panamax Locks are not constructed (continuation of the present situation). Provided that climate conditions and ship transit intensities remain as they are at present, current salinity levels in Gatun Lake and Miraflores Lake may be regarded as stable levels (with seasonal variations throughout the year). Present salinity levels are thus also valid for year 50. As an example the varying salinity levels of Miraflores Lake and Gatun Lake in the period 1 January 2011 – 31 December 2020 are shown in next figures.

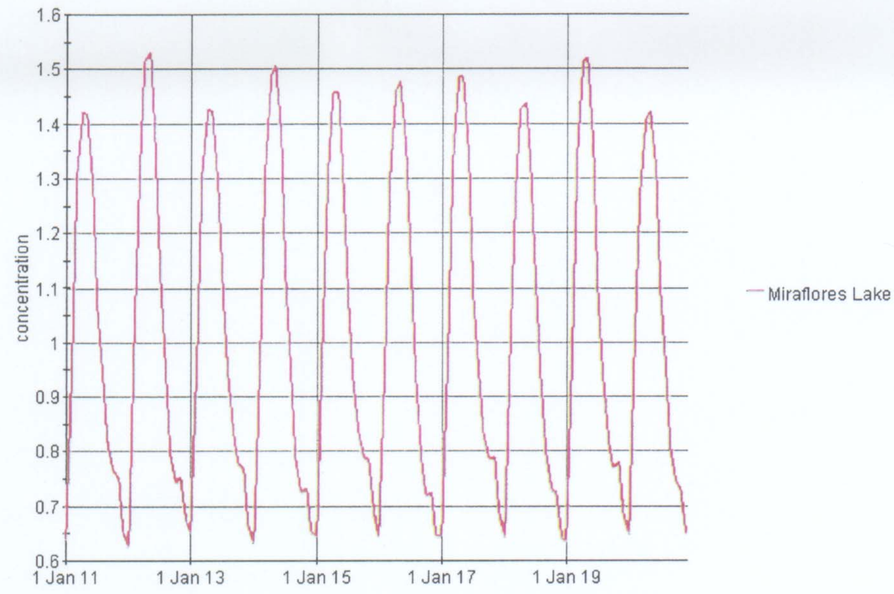


Figure 2.1 Volume-averaged salt concentration (ppt) Miraflores Lake, no Post-Panamax Locks, period 2011 – 2020 (output interval: month)

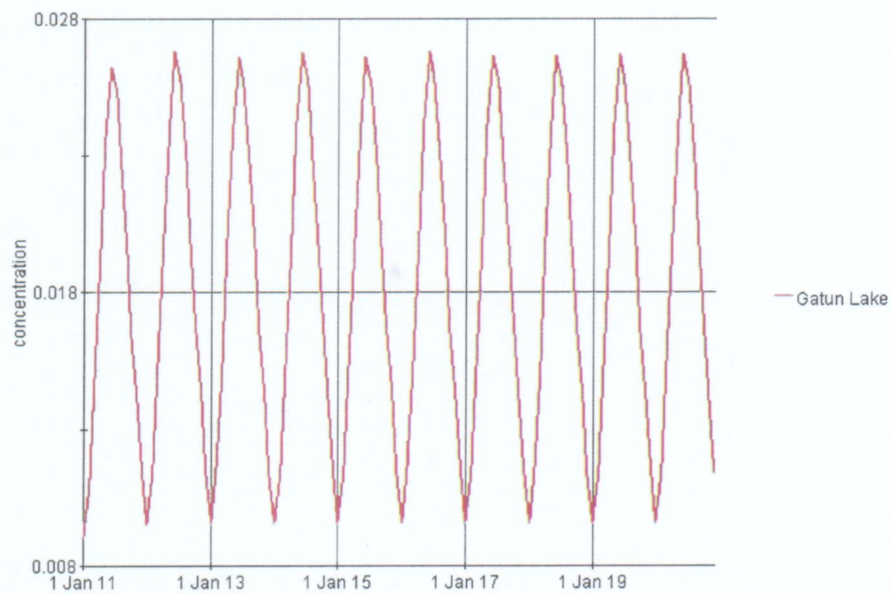


Figure 2.2 Volume-averaged salt concentration (ppt) Gatun Lake, no Post-Panamax Locks, period 2011 – 2020 (output interval: month)

An important question is which locks in the situation without Post-Panamax Locks contribute most to the salt intrusion in Gatun Lake: the locks at the Pacifc side or the locks at the Atlantic side. The simulation model can be used to answer that question. For year 50 we have executed computations for only a short period of time (May 1 – May 10, 2060) and have collected output after each ship movement. Results for upper lock chambers are shown in next figures.

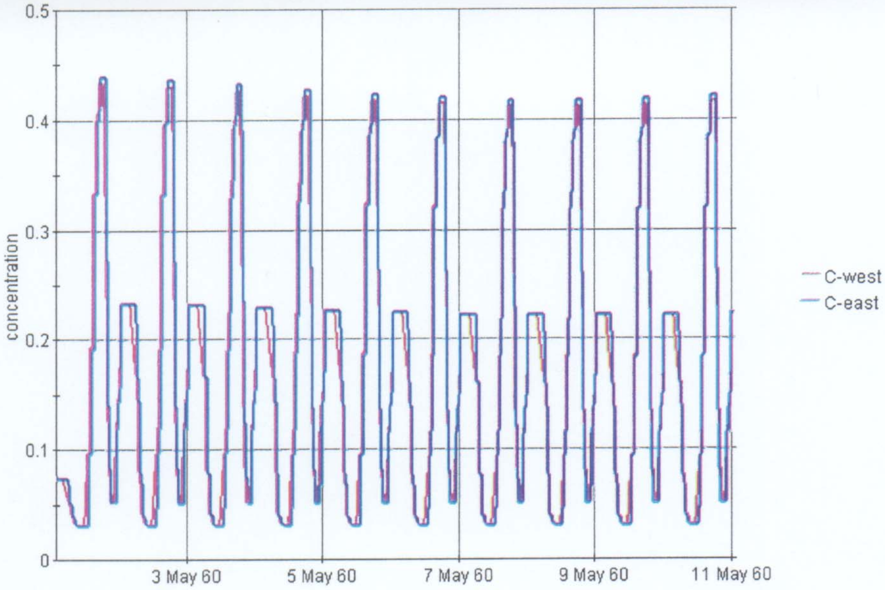


Figure 2.3 Volume-averaged salt concentration (ppt) upper lock chambers Pacific side, no Post-Panamax Locks, period May 2060, dry season (output interval: scenario)

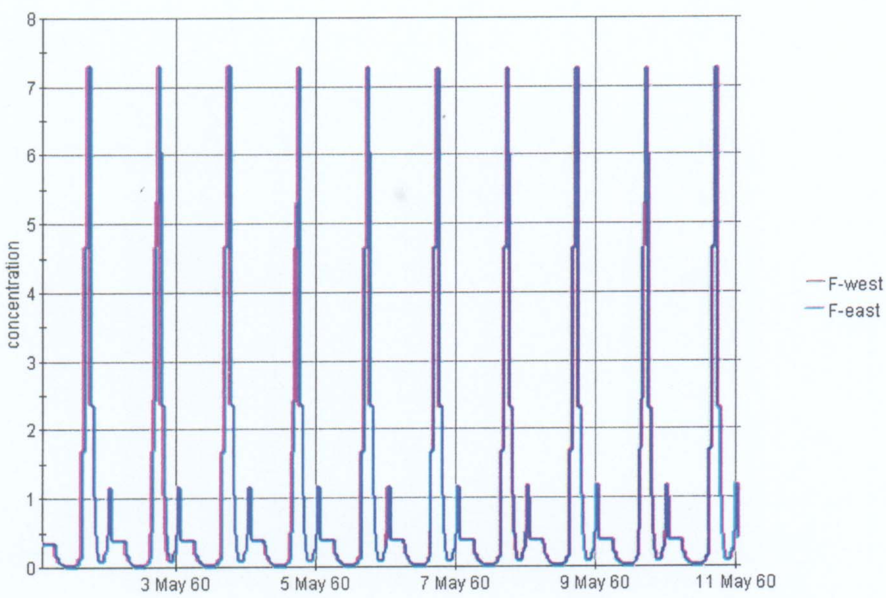


Figure 2.4 Volume-averaged salt concentration (ppt) upper lock chambers Atlantic side, no Post-Panamax Locks, period May 2060, dry season (output interval: scenario)

The daily variation of the volume-averaged salt concentration in the lock chambers, shown in Figures 2.3 and 2.4, is caused by the lockage operations and follows a certain pattern that is connected with the alternating series of uplocking and downlocking ships. As appears from the figures the salt concentration in the lock chambers decreases during uplockage of the first series of ships in the morning and increases sharply during downlockage of the next series of ships in the afternoon. The second, smaller series of uplocking ships in the evening causes a reduction of the salt concentration while the second, smaller series of downlocking ships at night causes again an increase. The effects of turn arounds in the upper lock chambers at the Atlantic side (Figure 2.4) are also visisble. It should be noted that salinity values during uplockage periods are valid for high water in the lock chamber (after filling of the chamber and exit of the ship to the lake), while values during downlockage periods are valid for low water in the chamber (after emptying and exit of the ship). The latter values are maximum values; minimum values may be a little smaller than the values shown in the figures for uplockage periods.

Most remarkable is the observation that the salt concentration values of the upper locks at the Atlantic side are considerably higher than those at the Pacific side. This can fully be attributed to the action of Miraflores Lake: this intermediate lake functions as a buffer for salt water between upper Miraflores Locks and Pedro Miguel Locks and also as a salt reductor, because salt water is regularly spilled away from Miraflores Lake through the outlets at Miraflores Dam. It functions also as a stabilizor and keeps the salt concentration values in Pedro Miguel Locks above a minimum value.
Figures 2.3 and 2.4 are valid for the end of the dry season, when salt concentrations in the lakes are highest, but similar differences between the locks at the Pacific and Atlantic side are also found for the wet season.
The computed, relative high salt concentration values in the upper locks at the Atlantic side were not observed during our site surveys. Though we have executed salinity measurements in these locks both during uplockage and downlockage of ships, we did not measure salinities at the end of a series of downlocking ships, when – as appears now from the numerical simulations - the salt concentration values are highest.

The fact that salt concentration values of the upper Atlantic locks are much higher than those of the upper Pacific locks means that at present more salt intrudes Gatun Lake through Gatun Locks than through Pedro Miguel Locks and Gaillard Cut.
In the future, when a new shipping lane has been excavated that by-passes Miraflores Lake, the smoothing effect of this buffer lake will reduce. As a consequence the Post-Panamax Locks at the Pacific side and the Post-Panamax locks at the Atlantic side will have a more equal impact on the salinity level of Gatun Lake. Simultaneously, the current, very low salinity level of Gaillard Cut may unfavourably be effected.

2.3 Salt water intrusion future situation with Post-Panamax Locks

Numerical simulations of the salt water intrusion have been executed for three configurations of Post-Panamax Locks, each configuration with an option to save water by means of separate water saving basins (wsb's). The various configurations, the scenarios for water supply to Gatun Lake in combination with saving of water at the locks, the ship traffic developments and the numerical modelling are described in Reports B, C and D.
The results of the simulations for year 50 after opening of the new shipping lane are presented in next section. Both the existing shipping lanes and the new shipping lane are in operation. Results are mutually compared also in relation to the present situation.

2.3.1 Salinity levels of Miraflores Lake and Gatun Lake in year 50

An overview of simulations for *year 50* is presented in Table 2.10. Ship traffic intensities in the two existing lanes have been kept constant during the considered period of 50 years: 18 ship transits per day per lane, equal to the present total number of 36 transiting ships per day. The traffic intensity in the third, new lane has grown to a number of 15 transiting Post-Panamax ships per day.

Configuration of Post-Panamax Locks	*Scenario 1 Baseline scenario. Wsb's in use.*	*Scenario 2 No wsb's.*	*Scenario 3 Wsb's in use. Reduction of water releases.*	*Scenario 4 No wsb's. Reduction of water releases.*
3-lift locks	B1-50	B2-50	B3-50	B4-50
2-lift locks	C1-50	C2-50	C3-50	C4-50
1-lift locks	D1-50	D2-50	D3-50	D4-50

Table 2.10 Overview of salt-water intrusion simulations for year 50

The following scenarios are studied:

- Scenario 1 (baseline scenario). In this scenario the wsb's of the new locks are in operation. All remaining water losses caused by ship lockages in the new shipping lane are compensated by extra water supplies to Gatun Lake (in addition to the present supplies). Water releases at Gatun Dam (spillway, hydropower plant) and Miraflores Dam (spillway, cooling water offtake) remain as in the present situation.
- Scenario 2. In this scenario the wsb's of the new locks are *not* applied; as a result a greater quantity of water is required for ship lockages. All water losses caused by lock operations in the new shipping lane are compensated by extra water supplies to Gatun Lake (in addition to the present supplies). Water releases at Gatun Dam (spillway, hydropower plant) and Miraflores Dam (spillway, cooling water offtake) remain as in the present situation. This scenario requires the greatest extra water supply to Gatun Lake.
- Scenario 3. The wsb's of the new locks are in operation. The water releases at Gatun Dam are reduced with the water loss quantities caused by the operation of the new locks. In the dry season, however, the water releases at Gatun Dam are small and extra water supplies to Gatun Lake are needed to compensate for the lockage losses. Water releases at Miraflores Dam remain as in the present situation. This scenario requires the smallest extra water supply to Gatun Lake.
- Scenario 4. The wsb's of the new locks are *not* applied. As much as possible, the water releases at Gatun Dam are reduced with the water loss quantities caused by the operation of the new locks, but extra water supplies to Gatun Lake are necessary, both in dry and wet season. Water releases at Miraflores Dam remain as in the present situation.

The extra water supplies to Gatun Lake, which are required to compensate for the water losses caused by lock operations in the new lane with Post-Panamax Locks, are shown for year 50 in Table 2.11. These water quantities are based on a number of 15 lockages per day and average water release quantities at Gatun Dam (as applied also in salt water intrusion simulations, see reports B, C and D). Clearly, scenario 3 is most favourable from the viewpoint of extra water supply to Gatun Lake. Compared to the two-lift locks and the single-lift locks the 3-lift locks are the most economical solution and require the smallest quantity of extra water.

Configuration of Post-Panamax Locks	*Month of Year 50*	*Scenario 1 Baseline Wsb's in use. (10^6 m^3/day)*	*Scenario 2 No wsb's. (10^6 m^3/day)*	*Scenario 3 Wsb's in use. Reduction of water releases. (10^6 m^3/day)*	*Scenario 4 No wsb's. Reduction of water releases. (10^6 m^3/day)*
3-lift locks	January	3.00	7.50	0.00	2.89
	February	3.00	7.50	2.40	6.90
	March	3.00	7.50	2.80	7.30
	April	3.00	7.50	2.84	7.34
	May	3.00	7.50	2.06	6.56
	June	3.00	7.50	0.00	3.87
	July	3.00	7.50	0.00	1.95
	August	3.00	7.50	0.00	0.92
	September	3.00	7.50	0.00	0.00
	October	3.00	7.50	0.00	0.00
	November	3.00	7.50	0.00	0.00
	December	3.00	7.50	0.00	0.00
2-lift locks	January	6.00	12.00	1.39	7.39
	February	6.00	12.00	5.40	11.40
	March	6.00	12.00	5.80	11.80
	April	6.00	12.00	5.84	11.84
	May	6.00	12.00	5.06	11.06
	June	6.00	12.00	2.37	8.37
	July	6.00	12.00	0.45	6.45
	August	6.00	12.00	0.00	5.42
	September	6.00	12.00	0.00	3.68
	October	6.00	12.00	0.00	3.77
	November	6.00	12.00	0.00	0.40
	December	6.00	12.00	0.00	0.00
1-lift locks	January	6.00	24.00	1.39	19.39
	February	6.00	24.00	5.40	23.40
	March	6.00	24.00	5.80	23.80
	April	6.00	24.00	5.84	23.84
	May	6.00	24.00	5.06	23.06
	June	6.00	24.00	2.37	20.37
	July	6.00	24.00	0.45	18.45
	August	6.00	24.00	0.00	17.42
	September	6.00	24.00	0.00	15.68
	October	6.00	24.00	0.00	15.77
	November	6.00	24.00	0.00	12.40
	December	6.00	24.00	0.00	11.37

Table 2.11 Extra water supplies to Gatun Lake in year 50 required for operation of Post-Panamax Locks

The computed salinity levels of Miraflores Lake and Gatun Lake in year 50 (maximum and minimum) are shown in Figure 2.5 and Figures 2.6 / 2.6a. For reasons of comparison also the salinity levels are shown when new locks are not realized (configuration A = existing canal system). All presented values concern volume-averaged salt concentrations (salinity in ppt). The fresh-water limit line shown in the figures, is set on a value of 0.45 ppt. Notice that 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).

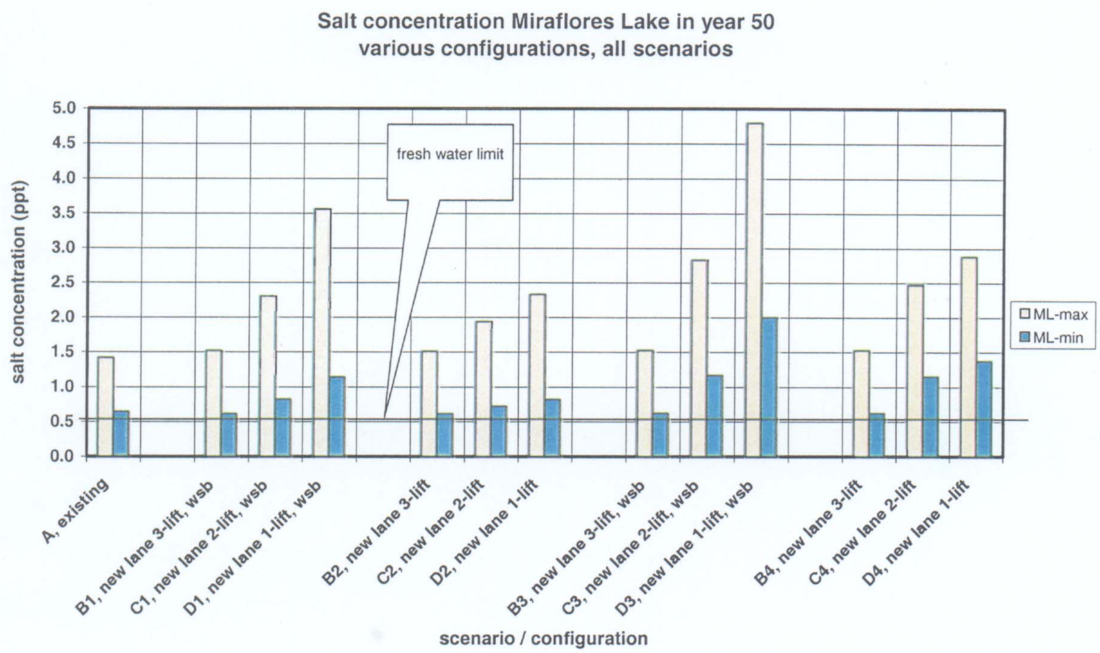


Figure 2.5 Volume-averaged salt concentration (ppt) Miraflores Lake, year 50

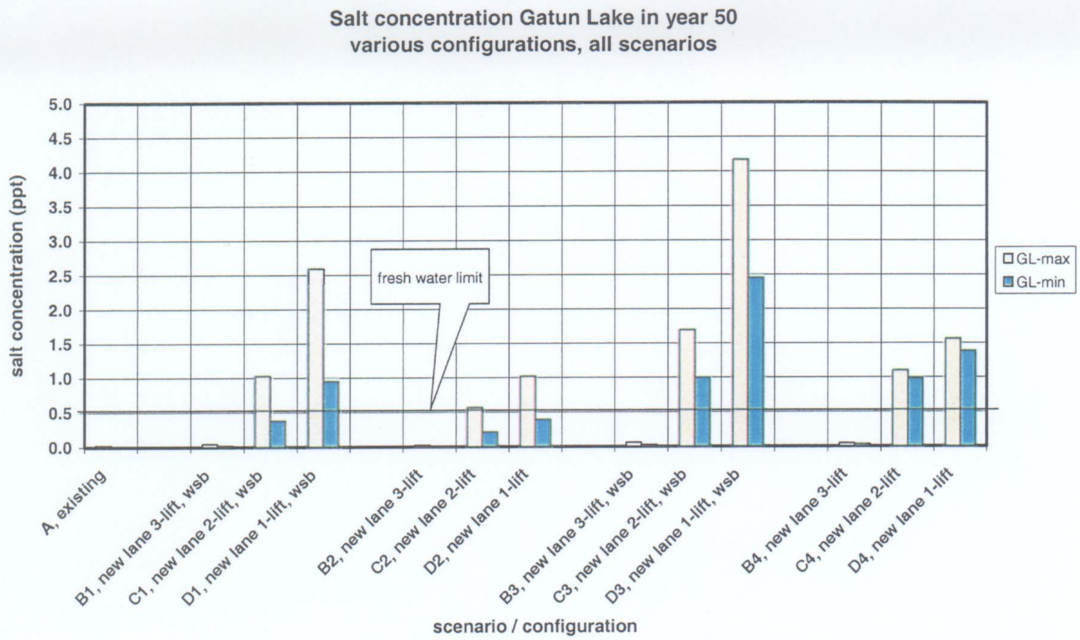


Figure 2.6 Volume-averaged salt concentration (ppt) Gatun Lake, year 50

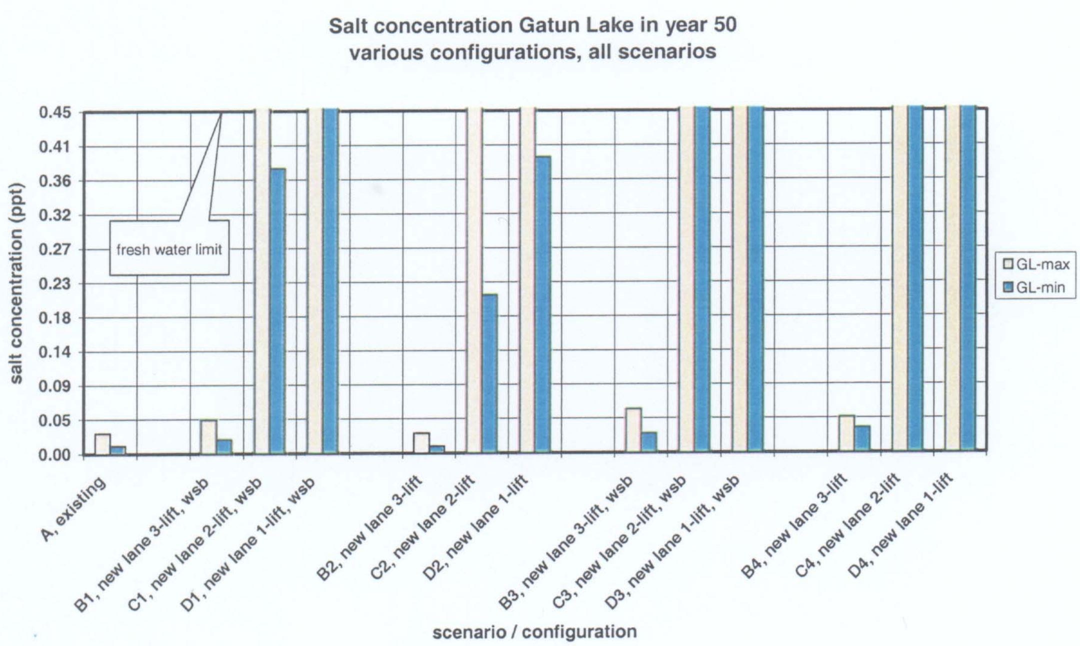


Figure 2.6a Volume-averaged salt concentration (ppt) Gatun Lake, year 50 (vertical scale adapted, so that values of configurations A and B1 can be viewed)

As can be read from Figures 2.5 and 2.6/2.6a the three-lift Post-Panamax Locks (simulations B) are very favourable from the view point of salt water intrusion in Gatun Lake; this conclusion is true for all four water saving / water release scenarios. Compared to the existing situation (A) the salinity of Gatun Lake increases slightly but the volume-averaged salt concentration remains far below the fresh water limit. However, because the salt does not disseminate and distribute equally over the full lake volume, areas with a higher salt concentration than the volume-averaged concentration will occur. Such areas may be Gaillard Cut, the shipping channel in the lake and the north-eastern area of the lake. This does not necessarily mean that the fresh-water limit in these areas is exceeded. A further study is required to assess whether local salinity levels rise above the fresh water limit. The salt concentration level in Miraflores Lake is hardly effected and remains more or less as in the present situation.

The single-lift Post-Panamax Locks (simulations D) are most unfavourable from the view point of salt water intrusion. The volume-averaged salt concentration of Gatun Lake rises far above the fresh-water limit in all four scenarios; local salt concentrations may even be higher. Also the salinity of Miraflores Lake is effected: the volume-averaged salt concentration increases in all four scenarios. Apparently, salt water is flushed back from Gaillard Cut through Pedro Miguel Locks into Miraflores Lake.

The effect of the two-lift Post-Panamax Locks (simulations C) on the salt concentrations of Gatun Lake and Miraflores Lake is not as strong as the effect of the single-lift locks, but is considerably stronger than the effect of the three-lift locks. Volume-averaged salt concentrations of Gatun Lake rise far above the fresh-water limit in all four scenarios, while also the volume-averaged salt concentration of Miraflores Lake increases.

From the measurements in the existing locks we know that the salt concentration levels of individual lock chambers in a series of adjacent locks with upward step in the floor are lower after each step. The total reduction will thus be greater in the case of the three-lift locks than in the case of the single-lift locks, or the two-lift locks. To learn more about the differences between the three lock alternatives we have compared the salt concentrations in the individual lock chambers during the various stages of the uplockage and downlockage process. The computed salt concentrations of individual lock chambers are compared in next section.

2.3.2 Salinity levels of individual lock chambers

Salt concentrations of individual lock chambers have been computed for year 50 after opening of the new lane. Salt-intrusion simulations were executed for a period of 10 days (May 1 – May 10, 2060) at the end of the dry season, when salt concentrations are highest. The salt concentration in lock chambers varies with high and low water in the chamber and also with uplockage and downlockage (see Section 2.2). Volume-averaged minimum and maximum salt concentration values in lock chambers of the existing locks and Post-Panamax Locks are shown in Tables 2.12 – 2.14 for the considered 10-day period in year 50 and scenarios 1 and 2. Table 2.15 shows the salt concentration values in the existing locks when Post-Panamax Locks are not constructed. In general, maximum values correspond to the situation with a low water level in the lock chamber, minimum values to the situation with a high water level.

Existing locks + 3-lift Post-Panamax Locks. Volume-averaged salt concentration in ppt.												
Lock system	*Existing locks Pacific side*			*Existing locks Atlantic side*			*Post-Panamax Locks Pacific side*			*Post-Panamax Locks Atlantic side*		
Lock chamber	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*	*K*	*L*	*M*
Scenario 1	8	1.5	0.05	2.5	0	0	14	2.5	0.2	16	4	0.5
	30	18	0.45	28	16.5	7.5	32	24	13.5	30	25	17
Scenario 2	8	1.5	0.05	2.5	0	0	7	0.5	0	7.5	0.5	0
	30	18	0.45	28	16.5	7.5	30.5	20	9.5	28	19	10.5

Table 2.12 Existing locks + 3-lift Post-Panamax Locks. Range of salt concentrations (in ppt) of individual lock chambers in year 50, end of dry season

Existing locks + 2-lift Post-Panamax Locks. Volume-averaged salt concentration in ppt.										
Lock system	*Existing locks Pacific side*			*Existing locks Atlantic side*			*Post-Panamax Locks Pacific side*		*Post-Panamax Locks Atlantic side*	
Lock chamber	*A*	*B*	*C*	*D*	*E*	*F*	*P*	*Q*	*R*	*S*
Scenario 1	9	2	0.8	3	0.5	0.5	14	2	13	2
	30	19	1.2	28	17	8	30	19	28	19
Scenario 2	9	2	0.5	3	0.5	0.5	9	1	8	1
	30	18	0.9	28	17	8	29	15	27	14

Table 2.13 Existing locks + 2-lift Post-Panamax Locks. Range of salt concentrations (in ppt) of individual lock chambers in year 50, end of dry season

Existing locks + 1-lift Post-Panamax Locks. Volume-averaged salt concentration in ppt.								
Lock system	*Existing locks Pacific side*			*Existing locks Atlantic side*			*Post-Panamax Locks Pacific side*	*Post-Panamax Locks Atlantic side*
Lock chamber	*A*	*B*	*C*	*D*	*E*	*F*	*N*	*O*
Scenario 1	10	3.5	2	4	2	2	16	15
	30.5	19	2.5	28	17.5	8.5	29	26.5
Scenario 2	9	2	0.8	3	1	1	7	6
	30	18.5	1.3	28	17	8	26	24

Table 2.14 Existing locks + 1-lift Post-Panamax Locks. Range of salt concentrations (in ppt) of individual lock chambers in year 50, end of dry season

Existing locks, no Post-Panamax Locks. Volume-averaged salt concentration in ppt.						
Lock system	*Existing locks Pacific side*			*Existing locks Atlantic side*		
Lock chamber	*A*	*B*	*C*	*D*	*E*	*F*
Existing situation	10	3.5	2	4	2	2
	30.5	19	2.5	28	17.5	8.5

Table 2.15 Existing locks (Post-Panamax Locks not realized). Range of salt concentrations (in ppt) of individual lock chambers in year 50, end of dry season

From the tables it appears that salt concentration values of most individual lock chambers of the existing locks (A – F, see also Reports B, C and D for names) do not importantly change when Post-Panamax Locks are in operation. The strongest effect occurs in Lock C (Pedro Miguel Locks) since the buffer function of the intermediate Miraflores Lake reduces when salt water directly intrudes Gatun Lake through the new locks.

For the salt intrusion into the lakes the phase of the lockage process with high water level in the upper lock chamber is of importance. This phase corresponds with the lower salt concentration values in the lock chambers. The lower values in the above tables are valid for uplockage of the last ship of a series of uplocking ships; these values are used for a mutual comparison of different lock systems:

Volume-averaged salt concentration in ppt.						
Side of canal	*Post-Panamax Locks Pacific side*			*Post-Panamax Locks Atlantic side*		
Lock system *Upper lock chamber*	*3-lift* *J*	*2-lift* *Q*	*1-lift* *N*	*3-lift* *M*	*2-lift* *S*	*1-lift* *O*
Scenario 1 wsb's in operation	0.2	2	16	0.5	2	15
Scenario 2 wsb's not in operation	0	1	7	0	1	6

Table 2.16 Post-Panamax Locks, upper lock chambers with high water level. Salt concentrations (in ppt) of individual lock chambers in year 50, end of dry season

Table 2.16 shows that the volume-averaged salt concentration of the upper lock chamber is smaller as the lock system has more upward steps in the floor. Salt concentrations are also smaller when wsb's are not in operation (scenario 2), but the differences between 1-lift, 2-lift and 3-lift locks remain. Since the salt concentration level in the upper locks is decisive for salt water intrusion, it appears that the greater the number of lifts the more effective salt intrusion in Gatun Lake is prevented.

2.4 Conclusions and recommendations

Both from the view point of salt water intrusion and extra water supplies to Gatun Lake the 3-lift Post-Panamax Lock system is the best alternative. The application of water saving basins helps to save water, but is also the cause of a somewhat greater salt water intrusion. The volume-averaged salt concentration of Gatun Lake remains far below the fresh-water limit, also when wsb's are in operation. However, areas with a higher salt concentration than the volume-averaged concentration will occur. Such areas may be Gaillard Cut, the shipping channel in the lake and the north-eastern area of the lake. This does not necessarily mean that the fresh-water limit in these areas is exceeded. A further study on the distribution of salt water in the lake is required to assess whether local salinity levels rise above the fresh water limit. If so, additional measures can be taken to reduce the salt water intrusion. The salt concentration level in Miraflores Lake is hardly effected and remains more or less as in the present situation.

The alternative 2-lift and 1-lift Post-Panamax Locks cause a much higher inflow of salt water into Gatun Lake. The volume-averaged salt concentration rises far above the fresh-water limit, also when wsb's are not in operation. These alternatives require additional measures to mitigate or prevent salt water intrusion.

Report B
Single-lift Post-Panamax Locks

Contents Report B

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I Introduction

The present Report B deals with the salt water intrusion of the *single-lift lock* configuration of Post-Panamax Locks on the future, third shipping lane. The salt water intrusion is additional to the salt water intrusion through the existing locks. The new single-lift locks may be provided with water saving basins.

The following items will be adressed in the present report:

- review of concept design of Consorcio Post-Panamax (CPP) for the *single-lift lock* configuration of Post-Panamax Locks;
- extension of the salt-water intrusion simulation model built for the existing situation with a new shipping lane; this new lane is is provided with *single-lift locks* and water saving basins at either side of the canal (the use of water saving basins is optional in the simulation model);
- selection of salt exchange coefficients that will be used in the simulation;
- simulation of salt water intrusion for the *single-lift lock* configuration of Post-Panamax Locks and analysis of results.

2 Concept design of CPP for single-lift lock configuration

2.1 Data provided by ACP

The next reports and drawings have been provided by ACP:

Report

Consorcio Post-Panamax (CPP)
'Diseño Conceptual de las Esclusas Post Panamax.
Conceptual design; Configuration 2: single-lift lock system;
Filling and emptying system'
Draft final report R4-C-420 rev C, 13 January 2003.

Drawings of CPP

Drawing number	Revision	Title
D4-A-201	-	Single lift configuration. General plan view.
D4-B-205	-	Single lift configuration. Cross-section Eastern lock wall.
D4-B-206	A	Single lift configuration. Cross-sections Western lock wall.
D4-B-207	-	Single lift configuration. Lock head 1. Plan view.
D4-B-210	A	Single lift configuration. Lock head 2. Plan view.
D4-B-211	A	Single lift configuration. Lock head 2. Longitudinal section.
D4-C-201	-	Single lift configuration. Water saving basins, filling and emptying system, structural design.
D4-C-202	-	Single lift configuration. 3D model water saving basins, filling and emptying system, hydraulic design.

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 lock system at Pacific side

The single-lift lock configuration of Post Panamax Locks designed by CPP, connects the canal entrance at the Pacific side with Gatun Lake (Gaillard Cut). We assume that similar as in the alternative three-lift lock system design a new channel will be excavated at the west side of Miraflores Lake, between the new lock and Gaillard Cut. This channel by-passes Miraflores Lake and forms a part of the new shipping lane. The new, single-lift lock is situated west of Miraflores Locks. The lock is provided with six water saving basins, arranged side by side at the east side of the lock.

The next data was taken by CPP as starting points for their design *(all levels refer to PLD)*:

Hydraulic conditions

Gatun Lake: mean water level +25.91 m, maximum water level +26.67 m, minimum water level +23.90 m.
Canal entrance at the Pacific side: mean sea level +0.30 m, extreme high tide +3.60 m, mean low tide –2.32 m, extrem low tide –3.44 m.

Lock chamber

Useful length of lock chambers 426.8 m, useful width 61.0 m, minimum water depth above sills 18.3 m. Locks can be operated with or without water saving basins; in the latter case water is directly transferred from forebay to lock and from lock to tailbay. The water saving rate is minimum 75% when water saving basins are in use. The filling or emptying time is approximately 35 minutes when water saving basins are in use, and 25 minutes when they are out of use.

Post-Panamax ships

Dimensions of ships: container ships 105,000 dwt and bulk carriers 140,000 dwt.

Single-lift lock design

The CPP-design for the single-lift lock configuration at the Pacific side of the canal is schematically shown in Figure 2.1. The new lock has a width of 61 m and the lock chamber is provided with a double set of rolling gates at both ends. The gates move in recesses, which are constructed in the floor of the lock chamber; the chamber floor is fully flat without sills. The nominal length of the lock chambers between the center line of the upper gates and the center line of the lower gates is about 480 m.
The step in the floor is 26.25 m high. Floor level –20.62 m of the lock is designed starting from the minimum required water depth of 18.3 m and a mean low-tide water level in the tailbay of –2.32 m. Floor level +5.63 m of the forebay in Gatun Lake follows from the minimum lake level +23.90 m and the minimum required water depth of 18.3 m.
Six water saving basins are arranged side by side along the lock chamber (see Figures 2.1 and 3.4). The length and width of the water saving basins differ from the horizontal dimensions of the lock chambers, but the capacity of the water saving basins is such, that at least 1/8 of the water exchange volume can be saved in each basin. The six water saving basins have different bottom levels, the lowest is situated at a level of +0.46 m, the highest at a level of +16.81 m.

The filling and emptying system consists of a multiport system. The main water culverts at both sides of the lock run along the full length of the lock from the intakes in the forebay to the outlets in the tailbay. The culverts are provided with valves to facilitate a controled flow of water from forebay to lock, and from lock to tailbay. Square openings (ports) connect the lock chamber with the culverts. The openings have dimensions of 1.8 m x 1.8 m and are situated in both lock walls (just above the floor) along the full chamber length, at a center to center distance of 15 m.

Each water saving basin (wsb) is connected to the longitudinal culverts by means of two gated transverse culverts (at about 1/3 and 2/3 of the chamber length). Filling of the lock chamber starts with emptying of the lowest wsb, and so on till the highest wsb. The remaining water portion is supplied from the forebay. Emptying of the lock chamber occurs in a reverse sequence: first the highest wsb is filled, and so on till the lowest wsb. The remaining water portion is discharged to the tailbay. Filling or emptying of a wsb stops when an equal water level is obtained in wsb and lock chamber. The same holds for the transfer of water from forebay to lock chamber and from lock chamber to tailbay.

2.3 Lock system at Atlantic side

Though the single-lift lock system has been designed by CPP for the Pacific side of the canal, we will assume, for the extension of the salt-water intrusion simulation model, that a similar lock system will be constructed at the Atlantic side. However, we will adapt the floor level of the lock because of the much smaller tidal variation at the Atlantic side of the canal (mean water level in the Atlantic entrance of the canal +0.06 m, extreme high tide +0.56 m, mean low tide –0.12 m, extrem low tide –0.38 m).
In the existing situation the difference between floor level of the lower locks at the Pacific side and the lower locks at the Atlantic side is about 2.0 m. When we start from extreme low tide at the Atlantic side of –0.38 m and a minimum required water depth of 18.3 m, a floor level of –18.68 m is found for the new, single-lift lock. In the schematization we assume a floor level of –18.62 m, 2.0 m higher than the floor level of the new lock at the Pacific side. The floor level of the forebay is +5.63 m, similar as at the Pacific side, giving a step height of 24.25 m. All other lock dimensions and the layout of water saving basins are similar as at the Pacific side, but the floor levels of water saving basins are adapted to the selected floor level and water levels of the lock chamber. The adopted single-lift lock system at the Atlantic side is shown schematically in Figure 2.2.

2.4 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 lane, which is provided with Post-Panamax locks at both sides of the canal. The vessels 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.

The daily traffic intensity (the total number of northbound and southbound ships) in the existing two lanes and the 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 2.1 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 has been set up for the existing situation (see description in Report A, issued June 2003) and is extended and adapted to the situation with a new shipping lane and single-lift locks. A scheme of the extended model is shown in Figure 3.1. The model predicts the salt water load on Gatun Lake and Miraflores Lake caused by locking 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, and being 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 the 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 (see Figures 3.5 and 3.6). 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, wsb's, forebays and tailbays of locks, lakes and entrances) are regarded as nodes in the numerical simulation model. The nodes and the hydraulic connections between the nodes are shown in the scheme of Figure 3.1. In the present study we name the locks as indicated in Figure 3.1. Locks in the existing lanes at the Pacific side are named: A-west and A-east, B-west and B-east, C-west and C-east; locks in the existing lanes at the Atlantic side are named: D-west and D-east, E-west and E-east, F-west and F-east. The single-lift locks in the new lane are named lock N at the Pacific side and lock O at the Atlantic side.

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.

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 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 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. A special scenario is the scenario that describes a 'turn around' (change from northbound ship transits to southbound ship transits or reverse), and a water-release scenario that describes the water spills and water use for hydropower generation and cooling.

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, for example for each day of the week. Subsequently, day patterns are combined in a case (see scheme of Figure 3.2). A case contains information on start date and stop date of the simulation. Day patterns are handled one by one in the sequence of input. After the last day pattern has been handled the simulation model starts again with the first day pattern; this cyclical process continues until the end of the simulation. The user shall prepare a set of salt exchange coefficients (see Chapter 4) 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 3.10). 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 3.3.

3.2 Single-lift locks and wsb's in simulation model

In addition to the two existing shipping lanes a new lane with single-lift locks at both sides is defined in the simulation model. Each lock is provided with water saving basins (wsb's). Because the six wsb's of a lock are filled or emptied one after another and the sequence of filling and emptying is always the same, the set of six wsb's can for the purpose of salt-water intrusion simulation be replaced by a single wsb (see Figure 3.4). The storage capacity of this single wsb is equal to the capacity of the set of six wsb's; also the fill and emptying time is equal to the fill- and emptying time of the set of six wsb's. The exchange coefficient in the salt balance is such selected that it is representative for the salt exchange between lock chamber and all six individual water saving basins (see Chapter 5). The locks in the new lane can be operated with or without wsb's in the simulation model.

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} (= $l_{lock} \cdot b_{lock}$)
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)

3.4 Ship movements and turn arounds; vessel classes

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 (see hereafter) between an uplockage and a downlockage scenario, but this is not required for ship movements in the new lane with single-lift locks.

With the new lane included a total number of 16 different ship movements and 8 turn arounds can be distinguished. The 1-lift locks in the new lane can be operated with or without water saving basins. Table 3.1 gives an overview of the various ship movements in the simulation model.

no	*ship movement*	*lane*	*up- or downlockage*	*remarks*
1	Pacific Ocean to Gatun Lake	west lane	Uplockage	
2	Gatun Lake to Pacific Ocean	west lane	Downlockage	
3	Pacific Ocean to Gatun Lake	east lane	Uplockage	
4	Gatun Lake to Pacific Ocean	east lane	Downlockage	
5	Pacific Ocean to Gatun Lake	new lane	Uplockage	wsb's out of use
6	Gatun Lake to Pacific Ocean	new lane	Downlockage	wsb's out of use
7	Pacific Ocean to Gatun Lake	new lane	Uplockage	wsb's in use
8	Gatun Lake to Pacific Ocean	new lane	Downlockage	wsb's in use
9	Atlantic Ocean to Gatun Lake	west lane	Uplockage	
10	Gatun Lake to Atlantic Ocean	west lane	Downlockage	
11	Atlantic Ocean to Gatun Lake	east lane	Uplockage	
12	Gatun Lake to Atlantic Ocean	east lane	Downlockage	
13	Atlantic Ocean to Gatun Lake	new lane	Uplockage	wsb's out of use
14	Gatun Lake to Atlantic Ocean	new lane	Downlockage	wsb's out of use
15	Atlantic Ocean to Gatun Lake	new lane	Uplockage	wsb's in use
16	Gatun Lake to Atlantic Ocean	new lane	Downlockage	wsb's in use

Table 3.1 Ship movements in simulation model

A turn around scenario describes the operational steps during a so-called 'turn around' (a change from northbound ship transits in a lane to southbound ship transits or reverse). In a turn around the water levels in the lock chambers are prepared for the change in ship transit direction. A total number of 8 different turn arounds for the existing lanes are distinguished in the simulation model (see Table 3.2). Turn arounds in the new lane with single-lift locks are not necessary.

no	*side of canal*	*turn around*	*lane*	*remarks*
1	Pacific side	change from northbound to southbound traffic	west lane	
2	Pacific side	change from southbound to northbound traffic	west lane	
3	Pacific side	change from northbound to southbound traffic	east lane	
4	Pacific side	change from southbound to northbound traffic	east lane	
5	Atlantic side	change from southbound to northbound traffic	west lane	
6	Atlantic side	change from northbound to southbound traffic	west lane	
7	Atlantic side	change from southbound to northbound traffic	east lane	
8	Atlantic side	change from northbound to southbound traffic	east lane	

Table 3.2 Turn arounds 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 3.3 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' is available for lockage operations without a ship.

The vessels which use the new shipping lane, are represented by three additional vessel classes (see Table 3.4). 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 2.1.

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

3.5 Steps in scenarios for ship movements

In this section the various steps in scenarios for ship movements in the new lane with a single-lift lock system are described. A distinction is made between locks without wsb's and locks with wsb's.

3.5.1 Locks without wsb's

Next table shows the subsequent steps in the uplockage scenario 'ship movement Pacific Ocean → Gatun Lake':

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

Table 3.5 Uplockage. Pacific Ocean → Gatun Lake. New lane, single-lift locks without wsb.

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 N	(Density flows)
Forebay Lock N	Lock N	Equalize water levels
Forebay Lock N	Lock N	Move ship
Lock N	Tailbay Lock N	Equalize water levels
Lock N	Tailbay Lock N	Move ship

Table 3.6 Downlockage. Gatun Lake → Pacific Ocean. New lane, single-lift locks without wsb.

The steps in the scenarios for ship movements Atlantic Ocean → Gatun Lake en Gatun Lake → Atlantic Ocean are similar, apart from the names of the locks (tailbay lock N = tailbay lock O, lock N = lock O, forebay lock N = forebay lock O).

3.5.2 Locks with wsb's

More steps are required in scenarios for ship movements in a single-lift lock system with wsb's. As an example next Table 3.7 shows the subsequent steps in the uplockage scenario 'ship movement Pacific Ocean → Gatun Lake' (see also Figure 3.5):

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

Table 3.7 Uplockage. Pacific Ocean → Gatun Lake. New lane, single-lift locks with wsb.

The subsequent steps in the downlockage scenario 'ship movement Gatun Lake → Pacific Ocean' are shown in Table 3.8 (see also Figure 3.6):

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

Table 3.8 Downlockage. Gatun Lake → Pacific Ocean. New lane, single-lift locks with wsb.

The steps in the scenarios for ship movements Atlantic Ocean → Gatun Lake and Gatun Lake → Atlantic Ocean are similar, apart from the names of the locks (tailbay lock N = tailbay lock O, lock N = lock O, forebay lock N = forebay lock O).

3.6 Steps in scenarios for turn arounds

A turn around scenario contains the various steps which are required to prepare the locks for a change in ship transit direction. However, in the case of a single-lift lock system no special measures have to be taken when the ship transit direction changes. For a description of turn arounds in the existing lanes reference is made to Report A.

3.7 Dimensions of locks, wsb's and forebays / tailbays

The characteristic dimensions of locks, wsb's and forebays in the new shipping lane are indicated in Table 3.9 (see also Figures 2.1 and 2.2).

basin	*nominal length* (m)	*width* (m)	*nominal, mean water level (m to PLD)* high	low	*flooor level = sill level* (m to PLD)	*step in floor* (m)	*coping level* (m to PLD)
Pacific side							
Lock N	480	61	+25.91	+0.30	-20.62	26.25	+29.67
wsb's Lock N					+0.46*		
Forebay Lock N			+25.91		+5.63		+29.67
Atlantic side							
Lock O	480	61	+25.91	+0.06	-18.62	24.25	+29.67
wsb's Lock O					+2.46*		
Forebay Lock O			+25.91		+5.63		+29.67

*) floor level of lower wsb

Table 3.9 Dimensions of single-lift locks, wsb's and forebays, new shipping lane

The characteristic dimensions of locks and forebays / tailbays in the existing lanes are shown in Table 3.10.

basin	*nominal length*	*width*	*nominal, mean water level (m to PLD)*		*floor level / sill level*	*step sill - sill*	*coping level*
	(m)	*(m)*	*high*	*low*	*(m to PLD)*	*(m)*	*(m to PLD)*
Pacific side							
Lock A (A-west & A-east)	329.2	33.5	+7.92	+0.30	-15.54 / -15.24	9.65	+9.75
Lock B (B-west & B-east	332.1	33.5	+16.46	+7.92	-6.20 / -5.59	9.04	+17.88
Forebay lock B (B-west & B-east)			+16.46		+3.35 (near intake) / +3.45		
Tailbay Lock C (C-west & C-east)			+16.46		+2.59 (near outlet) / +3.69		
Lock C (C-west & C-east)	332.1	33.5	+25.91	+16.46	+3.35 / +3.96	7.42	+28.04
Forebay lock C (C-west & C-east)			+25.91		+11.38 (near intake) / +11.38		
Atlantic side							
Lock D (D-west & D-east)	329.2	33.5	+8.54	+0.06	-13.51 / -12.90	8.76	+10.57
Lock E (E-west & E-east)	329.2	33.5	+17.38	+8.54	-4.67 / -4.14	8.71	+19.58
Lock F (F-west & F-east)	332.1	33.5	+25.91	+17.38	+4.17 / +4.57	6.81	+28.04
Forebay lock F (F-west & F-east)			+25.91		+4.27 (near intake) / +11.38		

Table 3.10　Dimensions of existing locks and forebays / tailbays

The dimensions and properties of basins in the simulation model are as follows:

New locks

The nominal lock chamber length is the size between the centre line of the upper gates and the centre line of the lower gates and equals about 480 m. The nominal length multiplied by the chamber width and the water-level difference determines the quantity of lockage water. Also the gate recesses contribute to the lockage water. This is accounted for by increasing the area of the lock chambers with the area of two gate recesses; doing so the nominal length of the lock chamber is increased with about 2 x 30 m, giving a total length of 540 m. This size is used in the numerical simulations. The new locks have flat floors without sills. Coping level corresponds to the top level of the lock walls.

Forebays new locks

The water volume of the forebays in Gatun Lake is arbitrarely computed as the product of length 540 m (= nominal lock chamber length + contribution gate recesses), width 61 m (= lock chamber width) and water depth above the adjacent lock floor. In formula form:

$V_{forebay} = A_{forebay} \, . \, (h_{lake} - f_{lock}) = 540 \text{ m} \, . \, 61 \text{ m} \, . \, (h_{lake} - f_{lock})$

Water saving basins new locks

The six wsb's of the 1-lift locks are replaced by a single wsb in the simulation model. The storage capacity of this single wsb is equal to the storage capacity of the six wsb's together. The salt exchange coefficient in the formulas that describe the exchange of salt water between single wsb and lock chamber is such selected, that it is representative for the exchange of salt water between the set of six individual wsb's and the lock chamber.

Existing locks

The nominal lock chamber length is the size between upper gate and lower gate of a lock This size determines the quantity of lockage water and is used in the simulations. Floor level corresponds to the flat, deeper part of the lock chambers; the sills protrude 0.3 m – 0.6 m (1 ft – 2 ft) above floor level. Lock chamber floors are thus at a lower elevation than the sills. Coping level corresponds to the top of the chamber walls.

Forebays and tailbays existing locks

The water volume of the forebays in Miraflores Lake and Gatun Lake and the tailbays in Miraflores Lake is arbitrarely computed as the product of length 330 m (= average nominal lock chamber length), width 33.5 m (= lock chamber width) and water depth above the adjacent lock sill. In formula form:

$V_{forebay} = A_{forebay} \, . \, (h_{lake} - f_{sill}) = 330 \text{ m} \, . \, 33.5 \text{ m} \, . \, (h_{lake} - f_{sill})$
$V_{tailbay} = A_{tailbay} \, . \, (h_{lake} - f_{sill}) = 330 \text{ m} \, . \, 33.5 \text{ m} \, . \, (h_{lake} - f_{sill})$

Function of forebays and taillbays 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 immediately be distributed over the full lake volume, which is not conform the real salt intrusion process. 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.
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.

In the simulations we put:

lock chambers:

V_{lock}	$= l_{lock} \cdot b_{lock} \cdot d_{lock}$ = water volume of lock chamber
l_{lock}	= nominal length of lock chamber (existing locks see Table 3.10, new locks 540 m)
b_{lock}	= width of lock chamber (existing locks 33.5 m, new locks 61.0 m)
h_{lock}	= water level (in m to PLD)
f_{lock}	= floor level (in m to PLD; see above Tables 3.9 and 3.10)
d_{lock}	= water depth in lock chamber $= h_{lock} - f_{lock}$
$maxh_{lock}$	= highest water level in lock chamber = coping level (in m to PLD)
$minh_{lock}$	= lowest water level in lock chamber; existing locks: sill level + 10 m (in m to PLD); new locks: floor level + 10 m (in m to PLD)

forebays (Gatun Lake, Miraflores Lake) and tailbays (Miraflores Lake) existing locks

$V_{forebay}$	$= 330\ m \cdot 33.5\ m \cdot (h_{lake} - f_{sill})$
$V_{tailbay}$	$= 330\ m \cdot 33.5\ m \cdot (h_{lake} - f_{sill})$

forebays new locks (Gatun Lake)

$V_{forebay}$	$= 540\ m \cdot 61\ m \cdot (h_{lake} - f_{lock})$

water saving basins new locks

V_{wsb}	$= l_{wsb} \cdot b_{wsb} \cdot d_{wsb}$
l_{wsb}	= length of wsb in simulation = 540 m
b_{wsb}	= width of wsb in simulation = 61 m
d_{wsb}	= water depth of wsb (total depth of the six individual wsb's)
$maxV_{wsb}$	= maximum water volume of wsb = 30 m x 540 m x 61 m = about 1000000 m^3
$minV_{wsb}$	= minimum water volume in wsb = 0.01 * $maxV_{wsb}$ (about 0.3 m water depth)

3.8 Miraflores Lake and Gatun Lake

3.8.1 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, evapotranspiration, 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 all month-averages (January, February, ... December) in this 10-year period were 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.
The same water levels are used as input in the simulation model for the new situation, after realization of the new shipping lane. The average water level values are shown in next table together with the corresponding water volume.

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 3.11 Gatun Lake: representative water level and corresponding water volume

The water levels of Gatun Lake and Miraflores Lake which are used in the simulation model are shown in Figure 3.7.

3.8.2 Water releases

The water levels of Miraflores Lake and Gatun Lake are controled by spillways. When the water level exceeds a maximum value, the surplus water is spilled. Water of Gatun Lake is also used for hydropower generation, water of Miraflores Lake for cooling.

The daily spilled water quantities of Gatun Lake and water quantities used for hydropower generation have been averaged for all months in the period 1992 – 2001. The average values of all month-averages (January, February, ... December) in this period were used in the validation of the simulation model (existing situation, see Report A); they were regarded as typical, representative values. Since the new shipping lane causes extra water losses, 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.

In a *baseline scenario* we start from the assumption that all extra water losses from Gatun Lake are compensated by an equal quantity of fresh water, that is supplied from new water sources. Consequently, the present water levels and water releases will not change and we will use the representative water-release quantities presented in Table 3.12 as input in the simulation model.

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 3.12 Gatun Lake: representative values of daily spilled water quantities and water quantities used for hydropower (baseline scenario)

In a *second scenario* we assume that the extra water losses caused by 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. The extra water losses of the new locks are growing when the Post-Panamax shipping intensity increases. Next Table 3.13 presents the extra water losses of the new locks; the values are based on the ship-traffic projections of ACP for the next 50 years (semi-convoy mode of operation) and on the assumption of 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 * 540 m * 61 m * 2 =

about 1.6 * 10^6 m^3 (with wsb's 0.4*10^6 m^3, 75% water saving). The water loss would be reduced with a factor 2 when alternate locking of ships (uplockage – downlockage) was applied, but this is contrary to the starting point that ships sail in semi-convoy mode.

Period after opening of new lane	*Post-Panamax ship transits (number per day)*	*Extra water losses (10^6 m^3/day)*	*Extra water losses in case of wsb's (10^6 m^3/day)*
month 1	2	3.20	0.80
year 1	5	8.00	2.00
year 5	6	9.60	2.40
year 10	7	11.20	2.80
year 20	9	14.40	3.60
year 50	15	24.00	6.00

Table 3.13 Extra water losses after opening of third, new lane with single-lift locks

In the *second scenario* the water releases at Gatun Dam are as follows (reduction for extra water losses of new lane with single-lift locks included):

Month	*Total water release year 0 (10^6 m^3 per day)*	*Total water release month 1 (10^6 m^3 per day)*	*Total water release year 1 (10^6 m^3 per day)*	*Total water release year 5 (10^6 m^3 per day)*	*Total water release year 10 (10^6 m^3 per day)*	*Total water release year 20 (10^6 m^3 per day)*	*Total water release year 50 (10^6 m^3 per day)*
January	4.61	1.41	0.00	0.00	0.00	0.00	0.00
February	0.60	0.00	0.00	0.00	0.00	0.00	0.00
March	0.20	0.00	0.00	0.00	0.00	0.00	0.00
April	0.16	0.00	0.00	0.00	0.00	0.00	0.00
May	0.94	0.00	0.00	0.00	0.00	0.00	0.00
June	3.63	0.43	0.00	0.00	0.00	0.00	0.00
July	5.55	2.35	0.00	0.00	0.00	0.00	0.00
August	6.58	3.38	0.00	0.00	0.00	0.00	0.00
September	8.32	5.12	0.32	0.00	0.00	0.00	0.00
October	8.23	5.03	0.23	0.00	0.00	0.00	0.00
November	11.60	8.40	3.60	2.00	0.40	0.00	0.00
December	12.63	9.43	4.63	3.03	1.43	0.00	0.00

Table 3.14 Gatun Lake: representative values of daily released water quantities (second scenario; single-lift locks without wsb's in new lane)

When the wsb's of the single-lift locks in the new lane are active the water losses are smaller and the water releases at Gatun Dam become:

Month	*Total water release year 0 (10^6 m^3 per day)*	*Total water release month 1 (10^6 m^3 per day)*	*Total water release year 1 (10^6 m^3 per day)*	*Total water release year 5 (10^6 m^3 per day)*	*Total water release year 10 (10^6 m^3 per day)*	*Total water release year 20 (10^6 m^3 per day)*	*Total water release year 50 (10^6 m^3 per day)*
January	4.61	3.81	2.61	2.21	1.81	1.01	0.00
February	0.60	0.00	0.00	0.00	0.00	0.00	0.00
March	0.20	0.00	0.00	0.00	0.00	0.00	0.00
April	0.16	0.00	0.00	0.00	0.00	0.00	0.00
May	0.94	0.14	0.00	0.00	0.00	0.00	0.00
June	3.63	2.83	1.63	1.23	0.83	0.03	0.00
July	5.55	4.75	3.55	3.15	2.75	1.95	0.00
August	6.58	5.78	4.58	4.18	3.78	2.98	0.58
September	8.32	7.52	6.32	5.92	5.52	4.72	2.32
October	8.23	7.43	6.23	5.83	5.43	4.63	2.23
November	11.60	10.80	9.60	9.20	8.40	8.00	5.60
December	12.63	11.83	10.63	10.23	9.83	9.03	6.63

Table 3.15 Gatun Lake: representative values of daily released water quantities (second scenario; single-lift locks with wsb's in new lane)

The daily water-release quantities of Tables 3.14 and 3.15 are used in the simulations.

The daily spilled water quantities of Miraflores Lake and the water quantities used for cooling at Miraflores are shown in Table 3.16. 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 3.16 Miraflores Lake: daily spilled / used water quantities in 2001

The values in Table 3.16 are not suited for use in the simulation model, because they are not representative for a longer period of time. To get better 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 0.075×10^6 m^3/day and a maximum value of 0.3×10^6 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 3.17; these values are regarded as representative values and are used in the simulation model. Since the new lane does not effect the water level of Miraflores Lake the water release quantities are valid both for the *baseline scenario* and the *second scenario.*

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 3.17 Miraflores Lake: representative quantities of daily spilled water and water used for cooling (baseline scenario and second scenario)

The daily water releases of Gatun Lake and Miraflores Lake (baseline scenario) are shown in Figure 3.8.

3.8.3 Effect of water level changes and water releases

Water levels and corresponding water volumes of Gatun Lake and Miraflores Lake are prescribed for each day of a case in the simulation model. Also the water-release quantities are prescribed through special water-release scenarios in the daypattern. The effects of water level changes on salt concentration of the lakes are evaluated at the start of each day; the effects of water releases are evaluated when the water-release scenarios are executed (see also Section 4.6).

3.9 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 absolute time (date, hour) in the simulation model. To that purpose sinusoïdal functions are applied. The resultant shape may not fully be conform the real water level fluctuation near the locks, but in the long run it are the period and the amplitude that count, rather than a full reproduction of the 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 = (2π/44760)
- ω_2 = frequency 2nd component = (2π/43233)
- t = time (s)

giving a minimum value of PLD –2.07 m and a maximum value of PLD +2.68 m (see Figure 3.9).

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 = (2π/44760)
- ω_2 = frequency 2nd component = (2π/43233)
- t = time (s)

giving a minimum value of PLD –0.14 m and a maximum value of PLD +0.26 m (see Figure 3.10).

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 3.18 Salt concentration in tailbays at Pacific and Atlantic side

The salt concentrations at the Pacific and Atlantic side, which are used in the simulation model are shown in Figure 3.11.

3.10 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. In addition, an initial value must be given to the salt concentrations in the lock chambers and wsb's, Miraflores Lake and Gatun Lake. To that purpose the user 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. Initial water levels in the lock chambers are by default selected from Tables 3.9 and 3.10 (nominal, mean high water level); initial water volumes of wsb's are by default set to '$minV_{wsb}$' (see Section 3.7).

4 Evaluation of nodal status parameters

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.
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, see Section 3.10. 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 Section 5) are prescribed through the input table 'Coefficient Set'.

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. 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 equations for ship movements and turn arounds in the *existing* shipping lanes are explained in Report A; they will not be repeated here.

4.1 Ship movements new lane, single-lift locks without wsb's

The evaluation of nodal status parameters for ship movements in the new shipping lane provided with a single-lift lock system without wsb's, is similar as described in Report A. Reference is made to Report A for a description.

4.2 Ship movements new lane, single-lift locks with wsb's, uplockage

Two 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); the wsb's of the lock are emptied or 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

The time-dependent exchange of salt water between forebays and lakes is handled in a 'special step'.

For the various combinations of basins (tailbays, locks with wsb's, forebays) the equations which describe the water balance and the salt balance within a basic step of the locking process are presented.

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

- the water volume V_{save} that is spilled to or supplied from the wsb's is equal to maximum 75% of the water volume V_{ref} that would be exchanged between lock and tailbay or forebay and lock when no wsb's were present
- consequently, the quantity of water that is exchanged between two adjacent basins amounts to: $V_{ref} - V_{save}$
- when wsb's get full or have insufficient water (this is checked in the simulation) a lesser quantity of water is transferred to and from the wsb's

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:

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

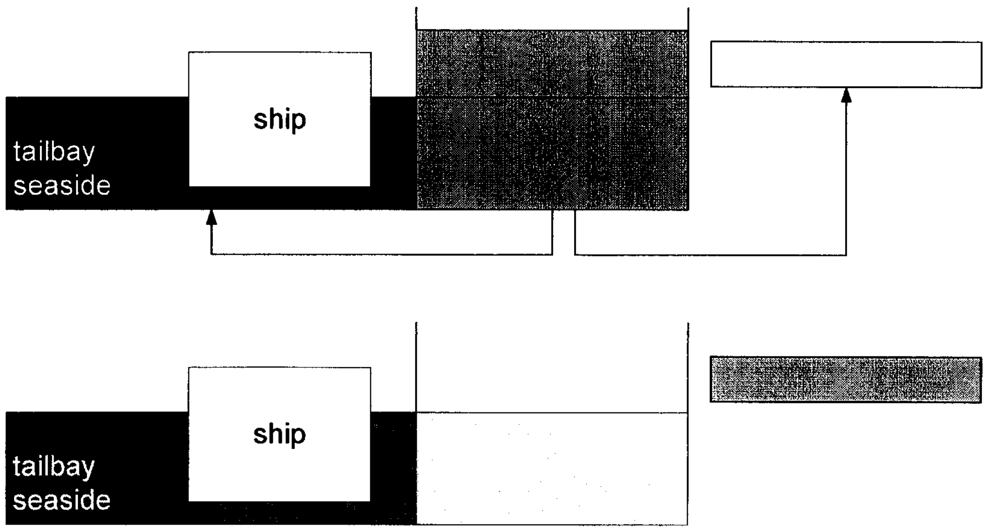
with:
e_{x0} = value of e_x for S = 0

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 that is filled, and salt withdrawal from the wsb 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

step I: the water level in the low basin (with ship) is equalized with the water level in the high basin (without ship); the wsb's of the lock are emptied or filled; water is transferred from high basin to low basin

low basin = tailbay seaside, high basin = lock



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

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

$V_{high2} = d_{high2} \cdot A_{high}$

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

$V_{save} = 0.75 \cdot V_{ref}$

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

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

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

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

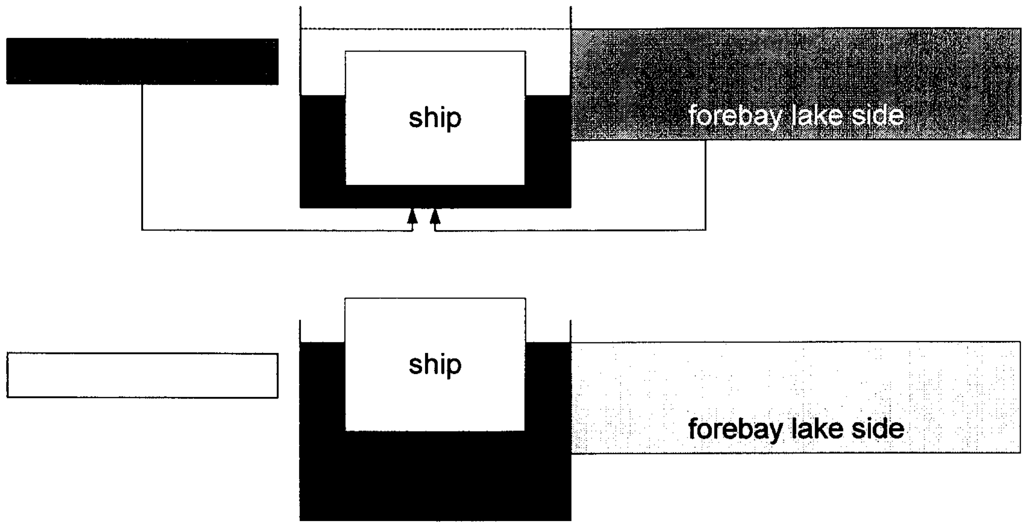
salt balance

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



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}, $V_{wsblow1}$

$h_{low2} \quad = h_{lake}$

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

if yes: $h_{low2} \quad = maxh_{low}$

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

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

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

$V_{low2} \quad = (d_{low2} \, . \, A_{low}) - S$

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

$V_{high2} \quad = V_{high1} = V_{forebay} = d_{high2} \, . \, A_{forebay}$

$V_{ref} \quad = (h_{low2} - h_{low1}) \, . \, A_{low}$

$V_{save} \quad = 0.75 \, . \, V_{ref}$

$V_{wsblow2} = V_{wsblow1} - V_{save}$

check: $V_{wsblow2} < minV_{wsblow}$?

if yes: $V_{wsblow2} = minV_{wsblow}$

$V_{save} \quad = V_{wsblow1} - V_{wsblow2}$

salt balance

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

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

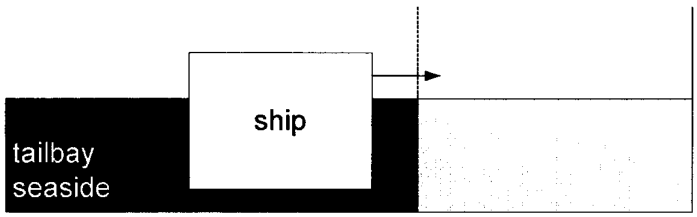
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

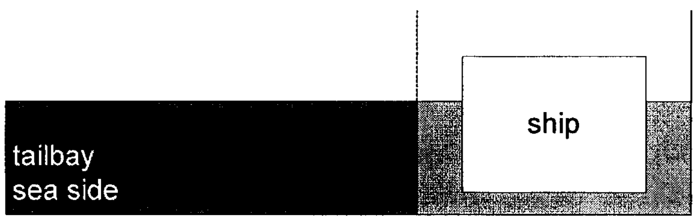
$$c_{wsblow2} = \frac{(V_{wsblow1} \cdot c_{wsblow1}) - (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1})}{V_{wsblow2}}$$

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

step II: the 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

low basin = tailbay sea side, high basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}

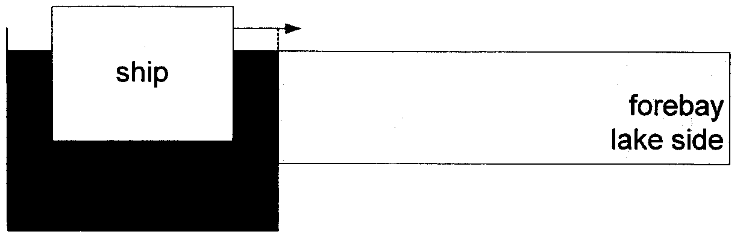
$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1}$$
$$V_{high2} = V_{high1} - S$$
$$V_{ref} = V_{high1}$$

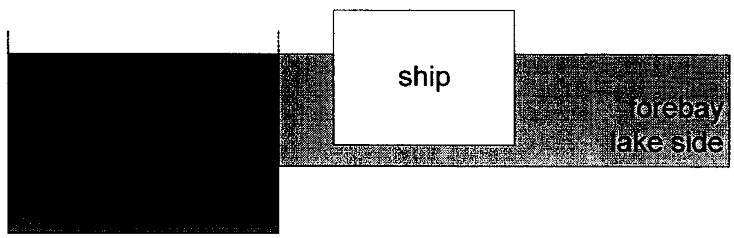
salt balance

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

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

low basin = lock, high basin = forebay lake side





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$$
\begin{aligned}
h_{low2} &= h_{low1} \\
d_{low2} &= d_{low1} \\
V_{low2} &= V_{low1} + S \\
h_{high2} &= h_{high1} \\
d_{high2} &= d_{high1} = d_{forebay} \\
V_{high2} &= V_{high1} = V_{forebay} \\
V_{ref} &= V_{high1}
\end{aligned}
$$

salt balance

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

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

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

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

Special step: exchange of salt water between forebay and lake

The forebay of the single-lift locks is in open connection with Gatun Lake. After an uplocking ship has passed the forebay the salt concentration in the forebay has changed. Density differences exist between the water in the forebay and the water in the lake, and as a result density-driven exchange flows occur. 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). 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} = 1 (full salt exchange)
Δt = time difference (s) between two subsequent ship passages
T = exchange time

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull} = 1$.
A period T = 3600 s is selected for the forebays in Gatun Lake starting from the assumption that the propagation velocity of a salt tongue is in the order of 0.1 – 0.2 m/s.

4.3 Ship movements new lane, single-lift locks with wsb's, downlockage

Two 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); the wsb's of the lock are emptied or 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

The time-dependent exchange of salt water between forebays and lakes is handled in a 'special step'.

For the various combinations of basins (tailbays, locks with wsb's, forebays) the equations which describe the water balance and the salt balance within a basic step of the locking process are presented.

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

- the water volume V_{save} that is spilled to or supplied from the wsb's is equal to maximum 75% of the water volume V_{ref} that would be exchanged between lock and tailbay or forebay and lock when no wsb's were present
- 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

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:

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

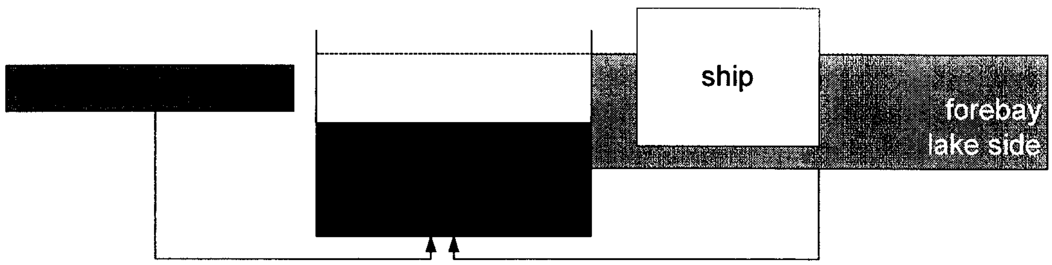
with:
e_{x0} = value of e_x for S = 0

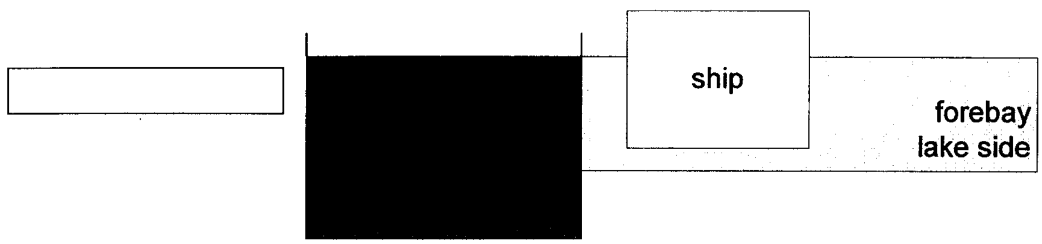
Definition of the exchange coefficient e_x:

- 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 that is filled, and salt withdrawal from the wsb 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

step I: the water level in the low basin (without ship) is equalized with the water level in the high basin (with ship) ; the wsb's of the lock are emptied or filled; water is transferred from high basin to low basin

high basin = forebay lake side, low basin = lock





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
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{save} = 0.75 \cdot V_{ref}$
$V_{wsblow2} = V_{wsblow1} - V_{save}$
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}, $c_{wsblow1}$

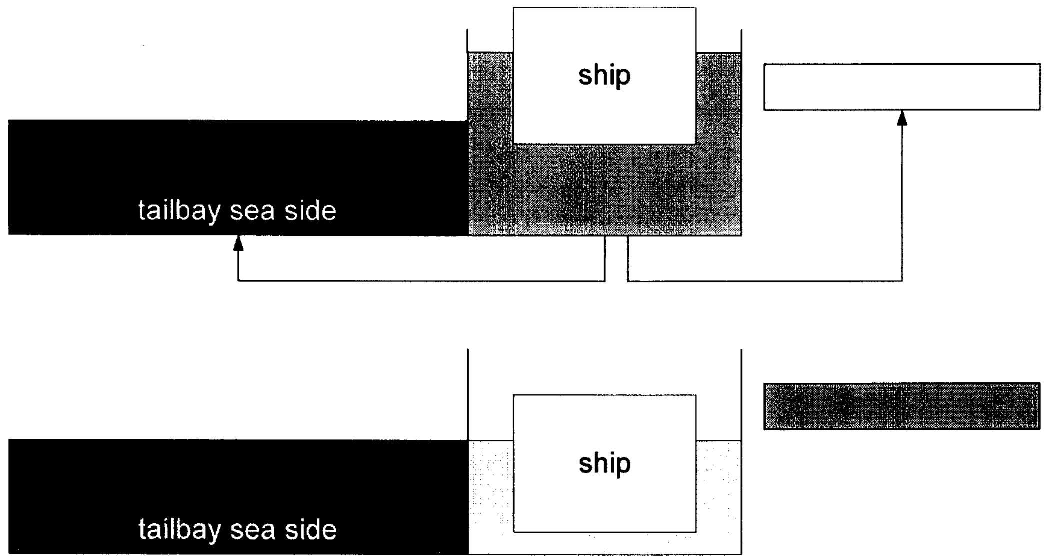
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

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

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

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

high basin = lock, low basin = tailbay sea



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} $= 0.75 \cdot V_{ref}$
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$
check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
V_{save} $= V_{wsbhigh2} - V_{wsbhigh1}$

salt balance

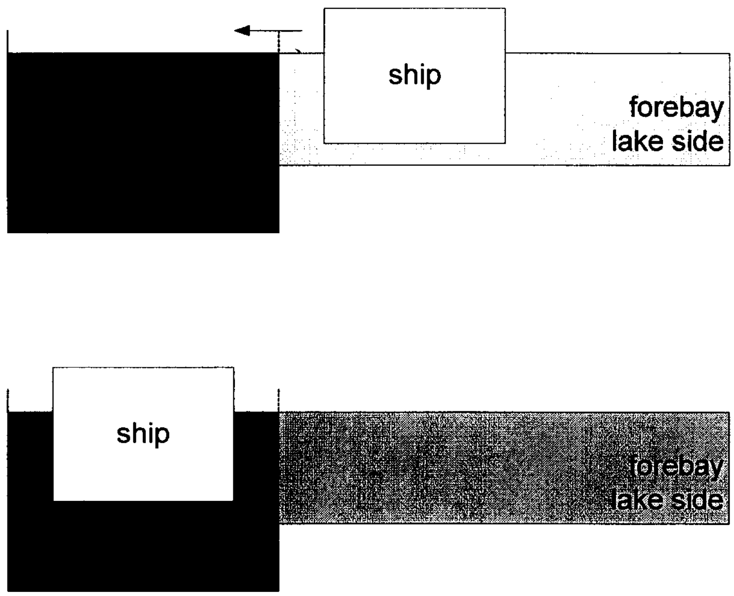
Known value at the beginning of step: c_{high1}, $c_{wsbhigh1}$

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

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

step II: the 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

high basin = forebay lake side, low basin = lock



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1} = d_{forebay}$$
$$V_{high2} = V_{high1} = V_{forebay}$$
$$h_{low2} = h_{low1}$$
$$d_{low2} = d_{low1}$$
$$V_{low2} = V_{low1} - S$$
$$V_{ref} = V_{high2} = V_{forebay}$$

salt balance

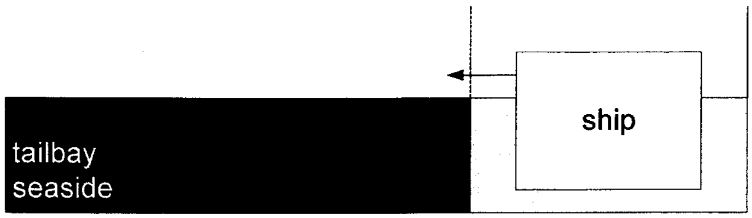
Known values at the beginning of step: c_{high1} ($= c_{forebay1}$), c_{low1}, c_{lake1}

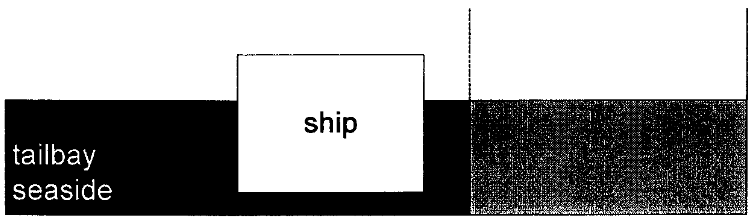
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) + e_x \cdot V_{ref} \cdot (c_{low1} - c_{high1}) + (S \cdot c_{low1}) - (S \cdot c_{high1})}{V_{high2}} = c_{forebay2}$$

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

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

high basin = lock, low basin = tailbay seaside





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}

$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1}$$
$$V_{high2} = V_{high1} + S$$
$$V_{ref} = V_{high2}$$

salt balance

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

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

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

The forebay of the single-lift locks is in open connection with Gatun Lake. After a down-locking ship has passed the forebay the salt concentration in the forebay has changed. Density differences exist between the water in the forebay and the water in the lake, and as a result density-driven exchange flows occur. 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 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). 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} = 1 (full salt exchange)
Δt = time difference (s) between two subsequent ship passages
T = exchange time

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull} = 1$.
A period T = 3600 s is selected for the forebays in Gatun Lake starting from the assumption that the propagation velocity of a salt tongue is in the order of 0.1 – 0.2 m/s.

4.4 Turn arounds new lane, single-lift locks

Turn arounds in the new shipping are not necessary in the case of a single-lift lock system (with or without wsb's).

4.5 Effect of water level changes of lakes and water releases

The water levels and corresponding water volumes of Gatun Lake and Miraflores Lake form input for the simulation model. The effect of water releases from the lakes on the water volumes is implied in the water levels, which are prescribed in the input table. The effect of water level changes of the lakes on the salt concentration is evaluated at the start of each day in the simulation.
Water releases (spillage of surplus water through Gatun Spillway and Miraflores Spillway, water for power generation, water for cooling) are prescribed through the water-release scenarios. The effect of the water releases on the salt concentration of the lakes is evaluated in the simulation, at the moment of time when the water-release scenarios are executed.

For a description of the evaluation of the effects of water level changes and water releases on the salt concentration of the lakes, reference is made to Report A.

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 that will be used in the simulation model for the future situation are selected on the experiences with the existing situation and on Delft3D density-flow computations for the single-lift lock.

5.1 Exchange coefficients when wsb's are in use

5.1.1 Delft3D computations

Delft3D computations have been executed for the filling and emptying process in the chamber of the single-lift lock, and for exchange flows and ship movements between tailbay and lock chamber and between lock chamber and forebay.

In order to restrict the number of grid cells and thus to keep computation times below reasonable limits the computation of the filling and emptying process is done for a 15 m wide section of the lock chamber. The size of 15 m is selected because the fill openings in both lock chamber walls are placed at a center to center distance of 15 m; the 15 m wide section thus contains two openings (in the center line of the section). This section model is regarded as a representative model for the full lock chamber.
In computations for exchange flows and ship movements a 2DV approach has been applied. Tailbay and forebay are modelled as basins with a length of 1000 m and a unit width; the lock chamber is modelled as a basin with length of 472 m and unit width. The boundary at the open end of tailbay and forebay was at first modelled as a full reflecting boundary; later the properties of the open end boundary were improved and the boundary was modelled as a non-reflecting boundary.

Lock chamber filling

A series of computations has been done aimed to simulate the filling process and the density currents in the lock chamber. In these computations the intial water depth was 20 m and the final water depth 45.5 m. The lock chamber was filled in 35 minutes (2100 s).
In one computation the initial salt concentration was 30 ppt at the floor and 20 ppt near the water surface (lineair decrease). The lock chamber was filled from six water saving basins, successively from lower basin, intermediate basins and upper basin with salt concentration 10 ppt, 12 ppt, 14 ppt, 16 ppt, 18 ppt and 20 ppt respectively, each contributing 12.5% to the the total fill-water volume; the remaining 25% was supplied from the higher lock and had a salt concentration of 0.5 ppt (these concentration values may be representative for filling of the lock chamber after opening and subsequently closure of the gates at the sea side).

The computation was repeated for the situation with the six individual wsb's replaced by a single one, with salt concentration of 15 ppt. The filling time was kept the same as the total filling time of the six individual wsb's. The computed volume-averaged salt concentration of the lock chamber during filling is shown in Figure 5.1 for these two configurations.
The figure indicates that with six wsb's the increase of salt concentration of the lock chamber is somewhat delayed, but after filling the concentration is equal in both situations.

More important is the comparison of the computed density-flow phenomena in the lock chamber, but these phenomena can not be read from the figure. The phenomena have been made visible by displaying the actual salt concentration distribution in the lock chamber at different moments of time as a series of consecutive 'snap shots'. This movie demonstrates that the water from the wsb's enters horizontally from both openings in the lock walls; in the center of the chamber (in between both lock walls) an upward movement develops which is accompanied by rotations in the vertical plane. The water in the lock chamber is roughly mixed up. After filling with water from the wsb's, water with a much lesser salt concentration is supplied from the forebay. The resulting upward water movement in the center of the lock chamber, at the location where the two jets meet, causes a further mixing up of the water in the lock chamber. As a result, the salt concentration becomes rather uniform at the end of filling (but the highest concentration is present near the floor).
It appears also that the single wsb causes comparable mixing phenomena in the chamber of the single-lift lock as the series of six separate wsb's, while also the final salt concentration distribution in the lock chamber is similar. From this we conclude that the six wsb's can be replaced by a single wsb in the simulation model, provided that salt-exchange coefficients are selected well.
When the water in the wsb's has a higher salinity than the receiving water in the lock chamber the fill water forms initially a lower layer in the lock chamber with higher salinity. During filling with less saline water from the forebay the entire water body in the lock chamber is mixed up (see also description in Report C), finally resulting in a rather uniform salt concentration distribution.

In the case that a ship (draught 14 m, beam 54 m) is present in the lock chamber the fill water from the wsb's spreads in the space under the ship and causes rotations and turbulences in the water. Finally, the inflow of less saline water from the forebay causes a full mixing up of the entire water body under the ship.

When the single-lift locks are compared with the three-lift locks (see Report C) it appears that the water in the deep chamber of the single-lift lock is mixed up during filling in a similar way as the water in the shallower lock chambers of the three-lift lock system. The salt concentration of the water in the chambers of the three-lift locks, however, reduces strongly after each upward step, which means that the upper lock chamber has a much lower salinity after filling than the chamber of the single-lift lock. This is an important observation, because it means that the salt concentration of the water in the single-lift lock is relatively high compared to the salt concentration of the water in the forebay. For this reason a much stronger salt water intrusion may be expected for Gatun Lake in the case of single-lift locks.

Lock chamber emptying

A series of computations have been made aimed to simulate the emptying process in the lock chamber. The initial water depth was 45.5 m and the final water depth 20 m. The lock chamber was emptied in 35 minutes (75% of the water was spilled into the wsb's and 25% into the tailbay).

In one computation the initial salt concentration in the lock chamber was 25 ppt near the floor and 5 ppt near the water surface (lineair decrease). These concentration values may be representative for emptying of the lower lock chamber after a ship has moved from the lock chamber to the forebay. The computed volume-averaged salt concentration of the lock chamber during emptying is shown in Figure 5.2. It appears that the decrease of the salt concentration is almost lineair. When we compute the quantity of salt that is transferred to successively upper wsb, intermediate wsb's and lower wsb, we find that these quantities rather well correspond to the quantities of salt that were present in the respective lower water layers in the chamber. In other words: during emptying the water is hardly mixed up; the water is mainly drawn from the lower water area and the vertical salt distribution in the remaining water volume does not change much. It also means that the upper wsb receives the water with highest salt concentration and the lower wsb the water with lowest salt concentration.

The density-flow phenomena have been made visible by means of a 'snap shot' movie. When emptying starts the water is drawn to the openings in both chamber walls. This process causes some transverse, internal waves from the center of the chamber to the sides and back, but the vertical distribution of the salt concentration is not strongly effected. Apparently, the water is mainly drawn from the lower water area. This withdrawal process is similar as was earlier found for the locks of the three-lift lock system.

The above computation was repeated with a ship (draught 14 m, beam 54 m) in the lock chamber. From the movie it appeared that the withdrawal of water from the space under the ship caused stronger density-flow effects than when no ship was present, in particular at the end of emptying, causing also some more mixing.

Exchange flows and ship movements

Delft3D computations have been made of the exchange flow between the tailbay and the lock chamber and between the forebay and the lock chamber in the case that a density difference is present. Also the effects of a moving ship (moving in 15 minutes from or into the lock chamber) have been simulated. Dimensions of the ship: ship type VII, Post-Panamax, draught 14 m, see Section 3.4.

The results of the Delft3D computations are discussed for next configurations:

- Configuration 'tailbay – lock chamber': water depth 20 m; initial salt concentration of tailbay 30 ppt, initial salt concentration of lock chamber 20 ppt.
- Configuration 'forebay – lock chamber': water depth in chamber 45.2 m, in forebay 20 m; initial salt concentration in the lock chamber 25 ppt near the floor and 5 ppt near the water surface (lineair decrease), initial salt concentration in the forebay 0.5 ppt.

The results for the tailbay – lock configuration are shown in Figure 5.3a (no ship), Figure 5.4a (uplocking ship) and Figure 5.5a (downlocking ship). The results for the forebay – lock configuration are shown in Figure 5.3b (no ship), Figure 5.4b (uplocking ship) and Figure 5.5b (downlocking ship). The figures present the volume-averaged salt concentration in upper and lower basin as a function of time. The density-flow phenomena have been made visible by means of a 'snap shot' movie.

Tailbay – lock chamber:

Exchange flows
Delft3D results are shown in Figure 5.3a. The 'snap shot' movie demonstrates that a salt tongue enters the lock chamber over the floor while simultaneously a tongue with lesser salinity and density enters the tailbay near the water surface. The propagation velocity of the two fronts is about 0.5 m/s. The salt tongue reflects against the closed end of the lock chamber and returns to the tailbay. It takes about 2000 s (33 minutes) for a full exchange, but near the water surface some water with lesser salinity remains in the lock chamber. The salt exchange coefficient e_x (indicated in Figure 5.3a) is derived making use of the formula's of Section 4.2. The value of e_x in the case of a full exchange is about 0.9.

Uplockage
The Delft3D computation has been repeated with an uplocking ship (Post-Panamax ship, ship type VII, results in Figure 5.4a). The 'snap shot' movie shows that a salt water tongue enters the lock chamber over the floor, but when the big ship enters the chamber the return current forces the salt water tongue to halt. Only when the ship is fully in the lock chamber, the salt water intrusion process resumes. The salt exchange coefficient e_x (Figure 5.4a) is via the quantity ($1- S/V_{ref}$) related to the net water volume in the lock chamber (see Section 4.2); e_x is relatively small shortly after the entrance of the ship, but grows as long as the tailbay gates are open. Due to the 2DV approach the coefficient e_x is possibly under-estimated (water with lesser salinity can not flow to the tailbay along both sides of the ship).

Downlockage
A similar computation has been executed for the case of a downlocking ship (Post-Panamax ship, ship type VII, results in Figure 5.5a). The 'snap shot' movie shows that the moving ship causes a salt return flow towards the lock chamber. A density current is generated in the lock chamber along the floor that reflects against the closed end of the chamber. The salt exchange coefficient e_x (Figure 5.5a) is related to the initial net water volume in the lock chamber (see Section 4.3; the ship's volume is replaced with salt water from the tailbay); the coefficient e_x has a higher value than in the case of uplockage.

Lock chamber – forebay

Exchange flows
Results of the Delft3D computation are shown in Figure 5.3b. The 'snap shot' movie shows that mainly the water body in the lock chamber above the level of the step is involved in the exchange process. A relative thin salt water tongue moves along the floor of the forebay and the water loss in the lock chamber is compensated by an inflow of less saline water from the forebay. Internal waves develop in the lock chamber below the level of the step, but mixing does hardly not occur. The salinity of the lock chamber (Figure 5.3b) decreases because of the exchange of water, but does not become equal to the lower salinity of the forebay; this is caused by the upward step, that prevents the salt water to escape from the lock chamber.

Uplockage
The computation with a Post-Panamax ship (ship type VII, results in Figure 5.4b) moving from lock chamber to forebay shows that the intrusion of salt water into the forebay is to a considerable extent prevented by the return current of the ship. From the 'snap shot' movie it appears that salt water mainly enters the forebay after the ship has exited the lock chamber.
The average salt concentration of the lock decreases during movement of the ship because of the return current (the ships volume is replaced by water from the forebay with lesser salinity). The salt exchange coefficient e_x shown in Figure 5.4b is related to the volume of the forebay in the simulation model (see Section 4.2), is small during movement of the ship and increases to a value of about 0.13.

Downlockage
In the case that a ship moves from forebay to lock chamber the return current sustains the intrusion of salt water into the forebay. Saltier water from the lock chamber is forced to flow into the forebay, but the involved water originates for the greater part from the water body above the level of the step, as is demonstrated by the 'snap shot' movie. Internal waves occur in the lock chamber, but do not cause important mixing. Figure 5.5b indicates that the average salt concentration of the lock chamber remains more or less constant, which means that also some saltier water from the water body below the level of the step enters the forebay. The exchange coefficient e_x shown in Figure 5.5b is related to the volume of the forebay (see Section 4.3) and increases to a value of 0.12 at the end of the ship movement, but this may be an under-estimate, due to the 2DV approach.

5.1.2 Selection of exchange coefficients

The hydraulic phenomena in the 1-lift locks of the new shipping lane have a strong resemblance with the hydraulic phenomena in the 3-lift locks (see Report C). Filling of a lock chamber through the openings in the chamber walls causes a mixing up of the full water body, while emptying does not importantly effect the vertical salinity profiles in the lock chamber. Exchange flows and effects caused by ship movements between tailbay and lock chamber are comparable because of the identical geometry. Also the exchange flows and ship movement effects between lock chamber and forebay have a high resemblance. The main difference is that the deep lock chamber of the 1-lift locks has a much higher salinity than the shallow upper lock of the 3-lift locks.
The intakes and outlets in forebays and tailbays have a similar location as in the 3-lift lock design.

On the basis of the results of the Delft3D computations and the insights obtained in the hydraulic processes, we select next exchange coefficients for step I of the lockage process ('equalize water levels'):

uplockage

fill wsb of lock:	$e_{fillwsb}$	= 1.25
empty wsb of lock:	$e_{emptywsb}$	= 1.0
equalize water levels:	e_x	= 1.05 (tailbay - lock)
equalize water levels:	e_x	= 0.95 (lock - forebay)

downlockage

fill wsb of lock:	$e_{fillwsb}$	= 1.1

empty wsb of lock: $e_{emptywsb} = 1.0$
equalize water levels: $e_x = 1.1$ (lock - tailbay)
equalize water levels: $e_x = 0.85$ (forebay - lock)

In the selection of the exchange coefficients for step II of the lockage process ('movement of ship') the opening time of the gates is of importance. The time required for opening of the gates, movement of the Post-Panamax ship and closure of the gates amounts to about 25 minutes. The *effective* opening time for exchange flows is smaller, about 15 - 20 minutes.
In the case of uplockage the gates connecting to the tailbay are, generally, opened far before the entrance of the ship; a total *effective* opening time of 25 minutes (1500 s) is a reasonable estimate. In the case of a downlocking ship the tailbay gates are closed immediately after exit of the ship. A total *effective* opening time of 15 minutes (900 s) is estimated.
An *effective* opening time of 15 minutes (900 s) is also assumed for the gates at the lake side, in the case of an uplocking ship. In the case of a downlocking ship we assume an *effective* opening time of 20 minutes (1200 s).

The exchange coefficients for step II are selected as follows.

Tailbay – lock, uplockage:
We select an exchange coefficient $e_x = 0.7$ for the exchange flows (similar as for the three-lift locks); this value corresponds to the salt water exchange after an opening time of the lock chamber of about 25 minutes (1500 s), see also Figure 5.3a.
The exchange coefficient $e_x = 0.7$ leads for the case of uplockage and the example shown in Figure 5.4a, with the quantity $1\text{-}S/V_{ref}$ about 0.5 (see also Section 4.2), to an effective salt exchange coefficient $e_x = 0.5 \times 0.7 = 0.35$. The value of e_x directly obtained from the Delft3D computation (Figure 5.4a) is smaller, about 0.2 after a period of 1500 s, but the 2DV approach is under-estimating e_x in this case because the water in the lock cannot flow along both sides of the ship to the tailbay.

Tailbay – lock, downlockage
An exchange coefficient $e_x = 0.4$ is selected for the exchange flows (similar as for the three-lift locks); this value corresponds to the salt water exchange after an opening time of the lock chamber of about 15 minutes (900 s), see also Figure 5.3a.
For the case of downlockage and the example shown in Figure 5.5a we find with $1\text{-}S/V_{ref}$ about 0.5 (see also Section 4.3) a value $e_x = 0.5 \times 0.4 = 0.2$ for the effective exchange coefficient. This agrees with the value of e_x that is directly obtained from the Delft3D computation (Figure 5.5a).

Lock – forebay, uplockage
An exchange coefficient $e_x = 0.05$ is selected for the exchange flows. This value is higher than selected for the three-lift locks (because of the greater density difference between lock chamber and forebay) and leads for the case of uplockage and the example shown in Figure 5.4b with the quantity $1\text{-}S/V_{ref}$ about 0.5 (see also Section 4.2) to an effective salt exchange coefficient $e_x = 0.5 \times 0.05 = 0.03$. The value of e_x obtained directly from a Delft3D computation for this case (Figure 5.4b) is a somewhat higher, 0.07, after a period of 900 s.

Lock – forebay, downlockage
An exchange coefficient $e_x = 0.15$ is selected for the exchange flows. Again, this value is higher than selected for the three-lift locks (because of the greater density difference

between lock chamber and forebay) and leads for the case of downlockage and the example shown in Figure 5.5b with the quantity 1-S/V_{ref} about 0.5 (see also Section 4.3) to an effective salt exchange coefficient e_x = 0.5 x 0.15 = 0.08. An equal value of e_x is obtained directly from a Delft3D computation for this case (Figure 5.4b) after a period of 1200 s.

It will be clear that uncertainties exists in the choice of representative exchange coefficients. For that reason we have executed a sensitivity analysis, in which we have varied the coefficients for step I and step II of the lockage process (see Section 7.4).

An overview of selected exchange coefficients for the 1-lift lock with wsb's at the Pacific side (lock N) is presented in Tables 5.1 and 5.2. Equal exchange coefficients are selected for the 1-lift lock (lock O) at the Atlantic side.
The combinations of exchange coefficients, which were varied in the sensitivity analysis, are also shown in the tables under Sens1 – Sens4.

Low basin	*High basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Tailbay Lock N	Lock N	Fill wsb's of lock N	1.25			1.0	1.5
Tailbay Lock N	Lock N	Equalize water levels	1.05			1.0	1.5
Tailbay Lock N	Lock N	Move ship	0.7*	0.5*	0.9*		
Lock N	Forebay Lock N	Empty wsb's of lock N	1.0				
Lock N	Forebay Lock N	Equalize water levels	0.95			0.7	1.2
Lock N	Forebay Lock N	Move ship	0.05*	0.0*	0.15*		
Forebay Lock N	Gatun Lake	(Density flows)	1.0**				

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

Table 5.1 Exchange coefficients uplockage. Pacific Ocean → Gatun Lake. New lane, single-lift locks with wsb.

High basin	*Low basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Gatun Lake	Forebay Lock N	(Density flows)	1.0**				
Forebay Lock N	Lock N	Empty wsb's of lock N	1.0				
Forebay Lock N	Lock N	Equalize water levels	0.85			0.6	1.1
Forebay Lock N	Lock N	Move ship	0.15*	0.05*	0.25*		
Lock N	Tailbay Lock N	Fill wsb's of lock N	1.1			1.0	1.4
Lock N	Tailbay Lock N	Equalize water levels	1.1			1.0	1.4
Lock N	Tailbay Lock N	Move ship	0.4*	0.3*	0.5*		

*) 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 5.2 Exchange coefficients downlockage. Gatun Lake → Pacific Ocean. New lane, single-lift locks with wsb.

5.2 Exchange coefficients when wsb's are not in use

In the case that the wsb's of the new locks are not in use the full quantity of lockage water is spilled into the tailbay and in a next cycle replenished by water drawn from the forebay. The exchange coefficients for spillage are such selected that they have a similar effect on the remaining water in the lock chamber as in the case that wsb's are in use. For the withdrawal of water from the forebay we apply an equal exchange coefficient as in the case that the wsb's are in use. The other exchange coefficients in step I and step II of the lockage process remain the same.

An overview of selected exchange coefficients for the lock (lock N) at the Pacific side is presented in Tables 5.3 and 5.4. Equal exchange coefficients are selected for the lock (lock O) at the Atlantic side. The combinations of exchange coefficients that are varied in the sensitivity analysis are also shown under Sens1 – Sens4 (see Section 7.4).

Low basin	*High basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Tailbay Lock N	Lock N	Equalize water levels	1.2			1.0	1.5
Tailbay Lock N	Lock N	Move ship	0.7*	0.5*	0.9*		
Lock N	Forebay Lock N	Equalize water levels	0.95			0.7	1.2
Lock N	Forebay Lock N	Move ship	0.05*	0.0*	0.15*		
Forebay Lock N	Gatun Lake	(Density flows)	1.0**				

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

Table 5.3 Exchange coefficients uplockage. Pacific Ocean → Gatun Lake. New lane, single-lift locks without wsb.

High basin	*Low basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Gatun Lake	Forebay Lock N	(Density flows)	1.0**				
Forebay Lock N	Lock N	Equalize water levels	0.85			0.6	1.1
Forebay Lock N	Lock N	Move ship	0.15*	0.05*	0.25*		
Lock N	Tailbay Lock N	Equalize water levels	1.1			1.0	1.4
Lock N	Tailbay Lock N	Move ship	0.4*	0.3*	0.5*		

*) 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 5.4 Exchange coefficients downlockage. Gatun Lake → Pacific Ocean. New lane, single-lift locks without wsb.

5.3 Other exchange coefficients

The exchange coefficients for the locks in the existing shipping lanes do not change after opening of the new, third shipping lane (for values of the exchange coefficients reference is made to Report A).

We also assume that the exchange coefficients related to the release of water at Gatun Dam and Miraflores are uneffected by the new shipping lane. The values of these exchange coefficients have been selected on the basis of validation runs for the existing situation (see report A). Maintaining equal exchange coefficients for the release of water offers also the possibility of a direct analysis of the third-lane related inflow of salt water into the lakes.

6 Testing of simulation model

The salt-intrusion simulation model for the existing situation has been extended with the single-lift locks in the new lane. The extension required the adaptation of formula in view of the water saving basins of the new locks, the definition of extra scenarios for ship movements, the definition of new Post-Panamax ship types, 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.

Input data
Test cases were such designed that the functioning of in particular the new items could be checked. Next Day Patterns and Coefficient Sets were used in the test runs:

Day Pattern	*Scenarios in day Pattern*	*Lane*
d1	Ship movement Pac. → Atl.; ship type 0	New, third (1-lift locks)
d2	Ship movement Atl. → Pac.; ship type 0	New, third (1-lift locks)
d3	Ship movement Pac. → Atl.; ship type VIII	New, third (1-lift locks)
d4	Ship movement Atl. → Pac.; ship type VIII	New, third (1-lift locks)
d5	Ship movement Pac. → Atl.; ship type VII	New, third (1-lift locks + wsb's)
d6	Ship movement Atl. → Pac.; ship type VII	New, third (1-lift locks + wsb's)
d7	Gatun Spillway; daily discharge = 5.10^6 m^3 Gatun Power Station; daily discharge = 5.10^6 m^3 Mirflaores Spillway (+cooling) ; daily discharge = 5.10^4 m^3	-
d8	Ship movement Pac. → Atl.; ship type VI	New, third (1-lift locks)
d9	Ship movement Atl. → Pac.; ship type VI	New, third (1-lift locks)
d10	Ship movement Pac. → Atl.; ship type V	New, third 1-lift locks)
d11	Ship movement Atl. → Pac.; ship type V	New, third (1-lift locks)
d12	Ship movement Pac. → Atl.; ship type IV	New, third (1-lift locks + wsb's)
d13	Ship movement Atl. → Pac.; ship type IV	New, third (1-lift locks + wsb's)
d14	Ship movement Pac. → Atl.; ship type III Ship movement Pac. → Atl.; ship type VIII Ship movement Pac. → Atl.; ship type VIII	West + East New, third (1-lift locks) New, third (1-lift locks + wsb)
d15	Ship movement Atl. → Pac.; ship type III Ship movement Atl. → Pac.; ship type VIII Ship movement Atl. → Pac.; ship type VIII	West + East New, third (1-lift locks) New, third (1-lift locks + wsb)

Table 6.1 Overview of Day Patterns used in test cases

Coefficient Set	*Up equalize*	*Up ship*	*Down equalize*	*Down ship*	*Up fill*	*Up empty*	*Down fill*	*Down empty*	*Exchange with lakes*	*Water releases*
c1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
c2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
c3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
c4	0.1	0.3	0.5	0.7	0.2	0.4	0.6	0..8	1.0	1.0
c5	0.5	0.2	0.5	0.2	0.5	1.0	0.5	1.0	1.0	1.0

Table 6.2 Overview of Coefficient Sets used in test cases

Test series A

A first series of tests was done with the salt concentration of all basins (including Pacific and Atlantic tailbays) set on 0. The purpose of these tests was to check the handling of water levels, water volumes, water displacement of new ship types and the set up of the water balance when a ship moves from ocean to ocean.

An overwiew of test cases of test series A is presented in Table 6.3.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
1	c1	d1	Jan 1 – Jan 31, 1970	scenario	single ship, S = 0
1-R	c1	d2	Jan 1 – Jan 31, 1970	scenario	single ship, S = 0
2A	c1	d3	Jan 1 – Jan 31, 1970	scenario	single ship, S = 285000
2A-R	c1	d4	Jan 1 – Jan 31, 1970	scenario	single ship, S = 285000
3A	c1	d5	Jan 1 – Jan 31, 1970	scenario	single ship, S = 260000
3A-R	c1	d6	Jan 1 – Jan 31, 1970	scenario	single ship, S = 260000

Table 6.3 Test cases series A: initial salt concentration is zero in all basins

Conclusions test series A

Water levels and water volumes, also those of the new basins in the simulation model, are well computed. Water transfer in the existing locks, new locks and wsb's caused by uplocking and downlocking ships is correct simulated and the water quantities fulfil the water balance.

Test series B

The set up of water balance and salt balance, the use of exchange coefficients, the time-dependent exchange of salt water between forebays and lakes, the proper functioning of spillways and the salt-water migration process from the lakes downwards has been checked in test series B. The initial salt concentration of Miraflores Lake and Gatun Lake was set on 30 ppt, the initial salt concentration of all other basins was set on 0.

An overwiew of test cases of test series B is presented in Table 6.4.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
4	c2	d7	Jan 1 – Dec 31, 1970	day	water releases
5A	c3	d1	Jan 1 – Jan 5, 1970	scenario	single ship, S = 0
5A-R	c3	d2	Jan 1 – Jan 5, 1970	scenario	single ship, S = 0
5B	c3	d8	Jan 1 – Jan 5, 1970	scenario	single ship, S = 200000
5B-R	c3	d9	Jan 1 – Jan 5, 1970	scenario	single ship, S = 200000
6	c4	d10	Jan 1 – Jan 5, 1970	scenario	single ship, S = 145000
6-R	c4	d11	Jan 1 – Jan 5, 1970	scenario	single ship, S = 145000
7	c4	d12	Jan 1 – Jan 5, 1970	scenario	single ship, S = 120000
7-R	c4	d13	Jan 1 – Jan 5, 1970	scenario	single ship, S = 120000
8	c5	d14	Jan 1 – Jan 5, 1970	scenario	several ships / all lanes
8-R	c5	d15	Jan 1 – Jan 5, 1970	scenario	several ships / all lanes

Table 6.4 Test cases series B: initial salt concentration of Gatun Lake and Miraflores Lake = 30 ppt, initial salt concentration of all other basins = 0

Conclusion test series B

The water balance and salt balance are well computed: salt water migrates properly from the lakes to all lower basins and to wsb's, the time-dependent exchange of salt water between forebays / tailbays and lakes is correct, the loss of salt water through water releases at Gatun Dam and Miraflores is well computed.

Test series C

In this third series of test cases the salt concentration of the tailbays at the Pacific and Atlantic side was set on 30 ppt. The aim of the tests was to check the salt-water intrusion from the seas into the lakes.

An overwiew of test cases of test series C is presented in Table 6.5.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
9	c5	d3	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
10-R	c5	d6	Jan 1 – Jan 5, 1970	scenario	single ship, S = 260000

Table 6.5 Test cases series C: initial salt concentration of Pacific and Atlantic tailbays = 30 ppt, initial salt concentration of all other basins = 0

Conclusion test series C

The water balance and salt balance are well computed: salt water migrates properly from the tailbays in the sea entrances to all higher basins and to wsb's, the time-dependent exchange of salt water between forebays / tailbays and lakes is correct.

As a last test the validation case for the existing situation (Case VAL1, see Report A) has been run as Case A-1 with the extended simulation model The extended model produced fully identical results, see Figures A-1, 1 and A-1, 2.

7 Salt water intrusion analysis future situation

In this section we present the results of the salt-water intrusion analysis for the future situation with a new, third shipping lane. Single-lift Post-Panamax locks are built at both ends of the new lane. The locks are provided with water saving basins (wsb's, see also Section 2). In the analysis we make a distinction between the situation that wsb's are not in use and the situation that the wsb's are used to prevent the loss of water from Gatun Lake. A comparison with the present salt-water intrusion through the existing locks concludes the analysis.
Starting point for the analysis is that the water levels in Miraflores Lake and Gatun Lake vary throughout the year as in the existing situation. In the baseline scenario the water releases (through Gatun Spillway, Gatun Power Station, Miraflores Spillway, Miraflores Cooling Water Offtake) remain as they are in the existing situation (which means that additional water is supplied to Gatun Lake to compensate for the extra losses via the new locks). In the second scenario the water releases at Gatun Dam are reduced with the water losses caused by shipping in the new lane. In the case that these water losses are greater than the water releases (this will in particular occur in the dry season) we assume that additional water supplies are available to replenish the surplus losses. The ship transit prospects for the next 50 years as given by ACP are used.

7.1 Data used in numerical simulations

The next data is applied in the numerical simulations:

- Dimensions of locks, forebays, tailbays, water saving basins: the dimensions presented in Section 3.7 are selected.
- Water levels and salt concentrations of seaside tailbays: values presented in Section 3.9 are selected.
- Water levels and corresponding water volumes, water releases of Miraflores Lake and Gatun Lake: values presented in Section 3.8 are selected.
- Initialization data: see Section 3.10
- Exchange coefficients: see Chapter 5.

7.2 Set up of cases for future situation

We assume that the new lane will come in operation at January 1, 2011. The present salt concentrations in Gatun Lake, Miraflores Lake and the locks on the existing shipping lanes are selected as initial salt concentrations. These salt concentrations have been obtained through numerical simulation of the salt water intrusion during a period of 10 years (validation run, see Report A), The initial salt concentrations in the new locks and wsb's are set to zero. This will probably not be conform the real situation, but as is shown the salinity values in the new locks and wsb's grow fast to an equilibrium value.

The salt intrusion in the future situation is analysed for a period of 1 month, 1 year, 5, 10, 20 and 50 years after opening of the third lane. Various cases have been set up to simulate the salt intrusion during these periods. Day patterns which are applied in the various cases, are such defined that they reflect the development of the ship traffic intensities in the next 50 years. In next table the daily number of transiting ships and the type of ships are presented for the various consecutive time periods. Panamax vessels are represented by ship type III, regular ships by ship types I and II, Panamax-Plus vessels by ship type IV, Post-Panamax vessels by ship type VII (draught 14 m, during first 5 years after opening of the new lane) and ship type VIII (draught 15.2 m).

	Jan 1, 2011 – Jan 31, 2011	*Febr 1, 2011 – June 30, 2011*	*July 1, 2011 – Dec 31, 2011*	*Jan 1, 2012 – Dec 31, 2012*	*Jan 1, 2013 – Dec 31 2015*	*Jan 1, 2016 – Dec 31 2020*	*Jan 1, 2021 – Dec 31 2025*	*Jan 1, 2026 – Dec 31 2030*	*Jan 1, 2031 – Dec 31 2040*	*Jan 1, 2041 – Dec 31 2050*	*Jan 1, 2051 – Dec 31 2060*
Vessel type	*Number of ships*										
Existing shipping lane West											
Type I	8	8	8	8	8	8	8	8	8	8	8
Type II	4	4	4	4	4	4	4	4	4	4	4
Type III	6	6	6	6	6	6	6	6	6	6	6
Total	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Existing shipping lane East											
Type I	8	8	8	8	8	8	8	8	8	8	8
Type II	4	4	4	4	4	4	4	4	4	4	4
Type III	6	6	6	6	6	6	6	6	6	6	6
Total	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Future third shipping lane (1-lift locks)											
Type IV	2	3	4	4	4	4	4	4	4	5	5
Type VII	0	0	1	2	0	0	0	0	0	0	0
Type VIII	0	0	0	0	2	3	4	5	7	9	10
Total	**2**	**3**	**5**	**6**	**6**	7	**8**	**9**	**11**	**14**	**15**
Simulations											
Period after opening of new lane	**1 month**	0.5 year	**1 year**	2 years	**5 years**	**10 years**	15 years	**20 years**	30 years	40 years	**50 years**

Table 7.1 Ship transits in simulation model in existing and new shipping lanes

In the set up of cases a distinction is made between 1-lift locks with and without wsb's, and 1-lift locks with and without wsb's and a reduced water release from Gatun Lake, see

Section 3.8 (water releases from Miraflores Lake remain as in the existing situation). The various cases are numbered as shown in Table 7.2.

In the baseline scenario we assume that all extra water losses caused by lock operation in the new shipping lane are compensated by extra water supplies to Gatun Lake, but water spills at Gatun Dam are not reduced. When the wsb's of the single-lift locks in the new lane are in use (Case D1) the extra water supply amounts to $0.4x10^6$ m^3 water per transiting ship (leading to an extra water supply in year 50 of 6.10^6 m^3 per day). When the wsb's are not applied (Case D2) the extra water supply to Gatun Lake amounts to $1.6x10^6$ m^3 water per transiting ship (leading to an extra water supply in year 50 of 24.10^6 m^3 per day).

In the second scenario we assume that the water releases at Gatun Dam are reduced with the water losses caused by the new locks. Consequently, a lesser quantity of fresh water has to be supplied to Gatun Lake. In the dry season, however, the spilled quantities are small or nil and extra water supplies are still needed to compensate for the water losses of the new locks (see also Tables 3.14 and 3.15). When wsb's are used (Case D3) the water loss is 75% smaller than when the wsb's are out of use (case D4).
For reasons of comparison we have also simulated the salt water intrusion in the period 2011 – 2020 when no new shipping lane is realised. This case is indicated with A-10.

Simulation time	Existing Situation	Future Situation 1-lift locks **with** wsb's (baseline)	Future Situation 1-lift locks **without** wsb's	Future Situation 1-lift locks **with** wsb's and reduced water releases GL	Future Situation 1-lift locks **without** wsb's and reduced water releases GL
1 month		D1-1m	D2-1m		
1 year		D1-1	D2-1	D3-1	D4-1
5 years		D1-5	D2-5		
10 years	A-10	D1-10	D2-10	D3-10	D4-10
20 years		D1-20	D2-20	D3-20	D4-20
50 years		D1-50	D2-50	D3-50	D4-50

Table 7.2 Overview of cases

For the new shipping lane with alternative 2-lift locks we reserve the letter C (see Report D). The alternative 3-lift locks have been discussed in Report C. The simulations for this alternative design are indicated with the letter B.

7.3 Results of simulations and analysis

The computed salt concentrations (ppt) of Miraflores Lake and Gatun Lake in the period year 2016 – year 2020 (ending 10 years after opening of new lane) and the period year 2051 – year 2060 (ending 50 years after opening) are shown in Figures D1-10, 1 through D4-50, 2. The results for the existing situation (no new lane) for the period year 2011 – year 2020 are shown in Figures A-10, 1 and A-10, 2. As can be seen the salt concentrations of Miraflores Lake and Gatun Lake fluctuate as a function of wet and dry season; the salt concentration levels stabilize within a period of about 1- 2 years after a change in ship traffic intensity.

The maximum and minimum values of the salt concentration of Miraflores Lake and Gatun Lake in the last year of the considered period are presented in Table 7.3.

Case	*Considered year*	*Salt conc. (ppt) Miraflores Lake*		*Salt conc. (ppt) Gatun Lake*	
		minimum	*maximum*	*minimum*	*maximum*
A-10	10	0.64	1.42	0.010	0.027
D1-1month	-	0.63	1.01	0.009	0.049
D1-1	1	0.63	1.66	0.009	0.36
D1-5	5	0.84	2.22	0.35	0.99
D1-10	10	0.87	2.32	0.42	1.18
D1-20	20	0.97	2.68	0.56	1.53
D1-50	50	1.14	3.56	0.95	2.59
D2-1month	-	0.63	1.00	0.009	0.031
D2-1	1	0.63	1.57	0.009	0.18
D2-5	5	0.72	1.81	0.16	0.45
D2-10	10	0.75	1.82	0.19	0.54
D2-20	20	0.79	2.02	0.25	0.67
D2-50	50	0.82	2.33	0.39	1.02
D3-1	1	0.63	1.87	0.009	0.70
D3-10	10	1.00	2.55	0.65	1.52
D3-20	20	1.22	3.08	0.99	2.13
D3-50	50	2.00	4.80	2.45	4.17
D4-1	1	0.63	1.65	0.009	0.45
D4-10	10	1.15	2.34	0.92	1.07
D4-20	20	1.31	2.64	1.16	1.30
D4-50	50	1.37	2.88	1.38	1.56

Table 7.3 Maximum and minimum values of salt concentration of Miraflores Lake and Gatun Lake

The maximum and minimum values are also shown in Figures 7.1 (Miraflores Lake) and 7.2 (Gatun Lake).

From Figure 7.1 it appears that depending on the scenario the salt concentration of Miraflores Lake increases with a factor up to 3.4 in year 50 compared to the present situation (scenario D3 is most unfavourable). Though Miraflores Lake is by-passed by the new lane, the new lane with Post-Panamax Locks has still an impact on the salinity of Miraflores Lake: extra salt water is spilled from Gatun Lake through Pedro Miguel locks into Miraflores Lake.

The salt concentration of Gatun Lake (Figure 7.2) changes considerably: the salt concentration increases from the present very low, negligible salinity level to a salinity level that raises above the fresh-water limit, similar as in Miraflores Lake. Notice that 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). The fresh-water limit line shown in the graphs is set on a value of 0.45 ppt salinity.

From Figures 7.1 and 7.2 it appears that Scenario D2 (no wsb's, no reduction of water releases at Gatun Dam) is most favourable in view of salt-water intrusion. The reason is that large quantities of fresh-water are supplied to Gatun Lake to maintain the water level of the lake. When wsb's are in operation (Scenario D1) a 75% smaller fresh-water supply is required and we see that the salt concentration levels increase. The salt concentration levels increase further when the water releases at Gatun Dam are reduced (Scenarios D3 and D4).

It should be noted that the computed concentration values are volume-averaged values, which means that local salt concentration values may be higher.

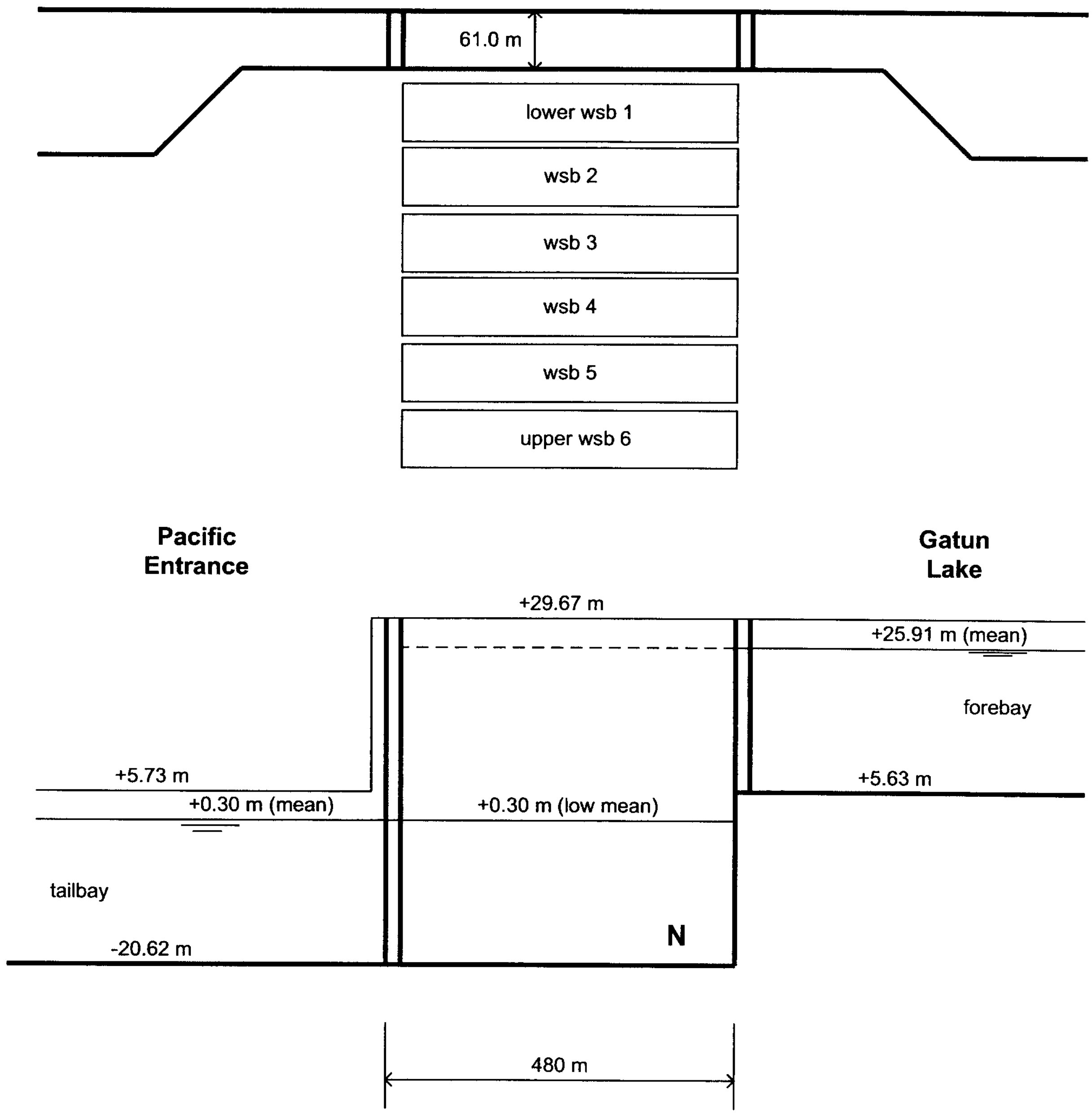
From the results of the simulations we conclude that the single-lift locks are unfavourable both from the view point of fresh water supply to Gatun Lake and salt water intrusion.

7.4 Sensitivity analysis

In a sensitivity analysis we have studied the effects of a variation of exchange coefficients for the single-lift locks in the new shipping lane. Most important coefficients are those which determine the exchange of salt water in step II of the uplockage and downlockage process (movement of ship between lock chamber and tailbay or forebay). These coefficients have been varied in cases Sens1 and Sens2. The exchange coefficients which determine the salt water transfer in step I of the uplockage and downlockage process (equalize water levels tailbay – lock or lock – forebay) have been varied in Sens3 and Sens4. For the values of exchange coefficients see Sections 5.1 and 5.2. The exchange coefficients of the existing locks have been kept constant (they are such selected that the salinity levels of Miraflores Lake and Gatun Lake in the present situation are correctly predicted, see also Report A).

The results of the sensitivity analysis are shown in Figure 7.3 (Miraflores Lake) and Figure 7.4 (Gatun Lake). These figures present the salt concentration of the lakes for the base exchange coefficients and for variations of the exchange coefficients. The figures demontrate that the salt concentration of the lakes varies with the exchange coefficients, but this variation is relatively small compared to the effects of the single-lift locks on the salinity of, in particular, Gatun Lake. The tendency of a much higher salinity level of Gatun Lake in the case of single-lift locks (with or without wsb's) is therefore reliable.

Figures

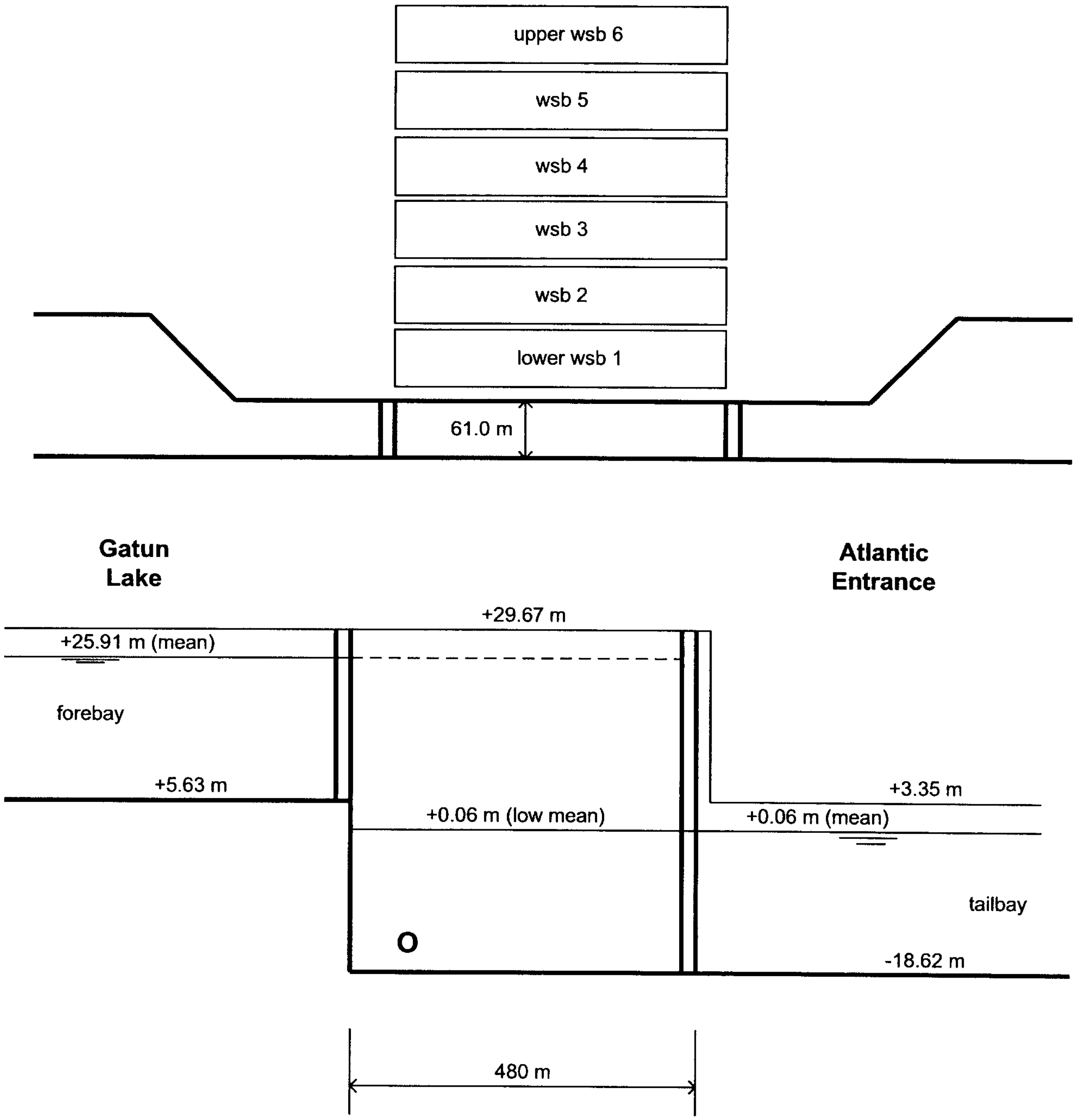


DESIGN OF 1-LIFT POST-PANAMAX LOCKS OF CPP
FOR PACIFIC SIDE, SHOWN SCHEMATICALLY

WL | DELFT HYDRAULICS

Q 3039

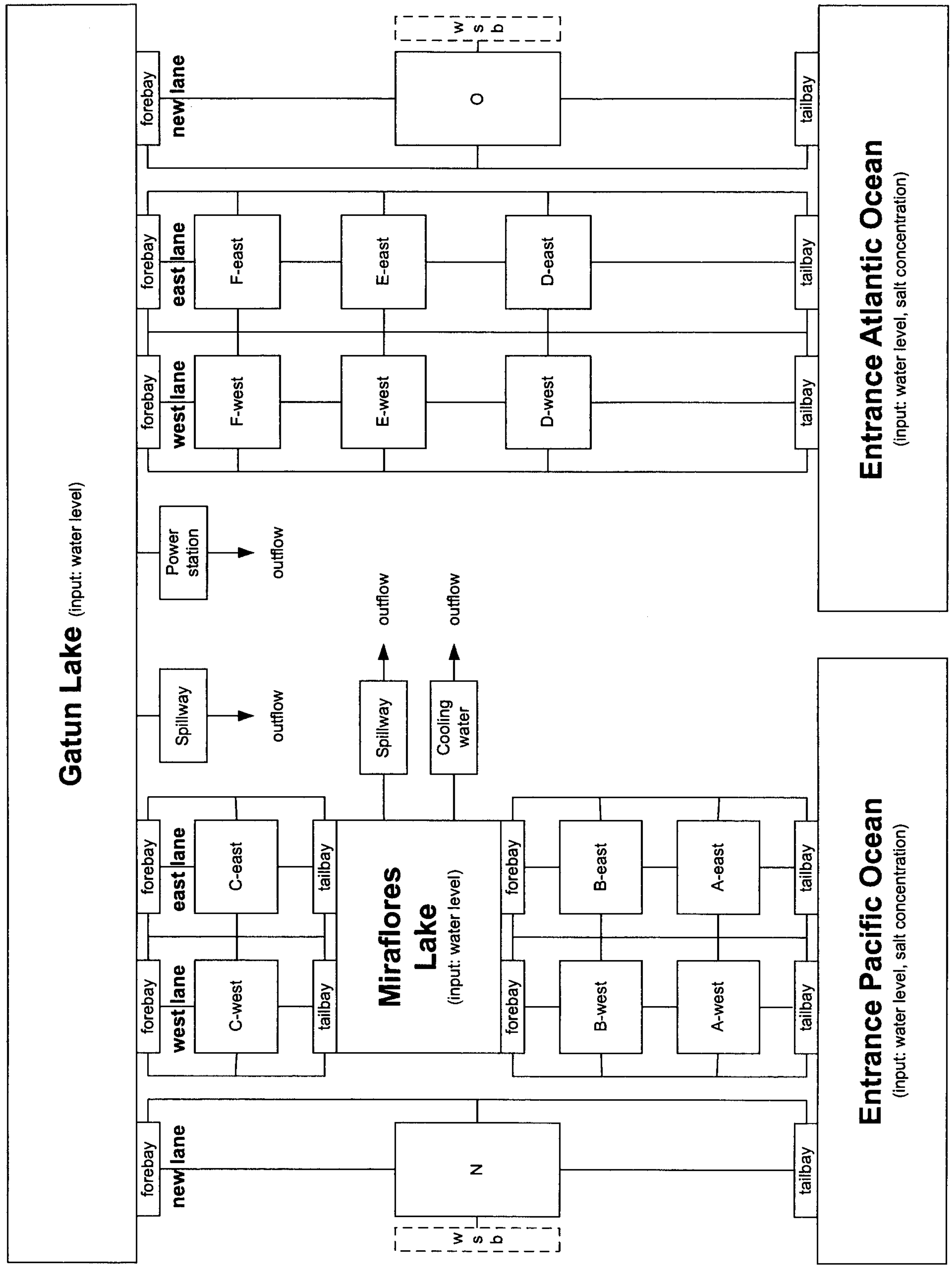
Fig. 2.1



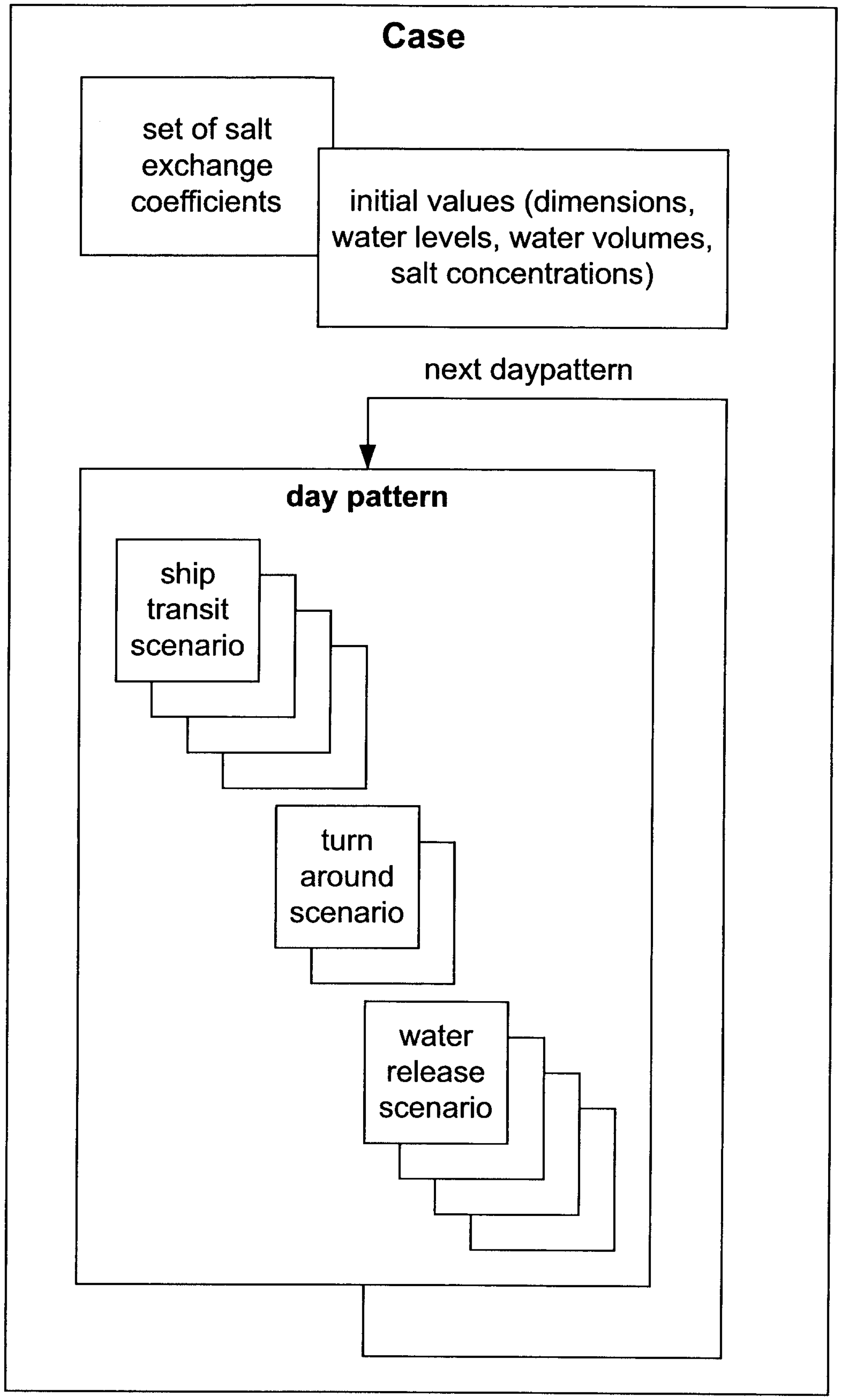
ASSUMED DESIGN OF 1-LIFT POST-PANAMAX LOCKS
FOR ATLANTIC SIDE, SHOWN SCHEMATICALLY

WL | DELFT HYDRAULICS

Q 3039 | Fig. 2.2



SIMULATION MODEL WITH NEW LANE AND 1-LIFT LOCKS. NODES AND HYDRAULIC CONNECTIONS		
WL | DELFT HYDRAULICS	Q 3039	Fig. 3 .1

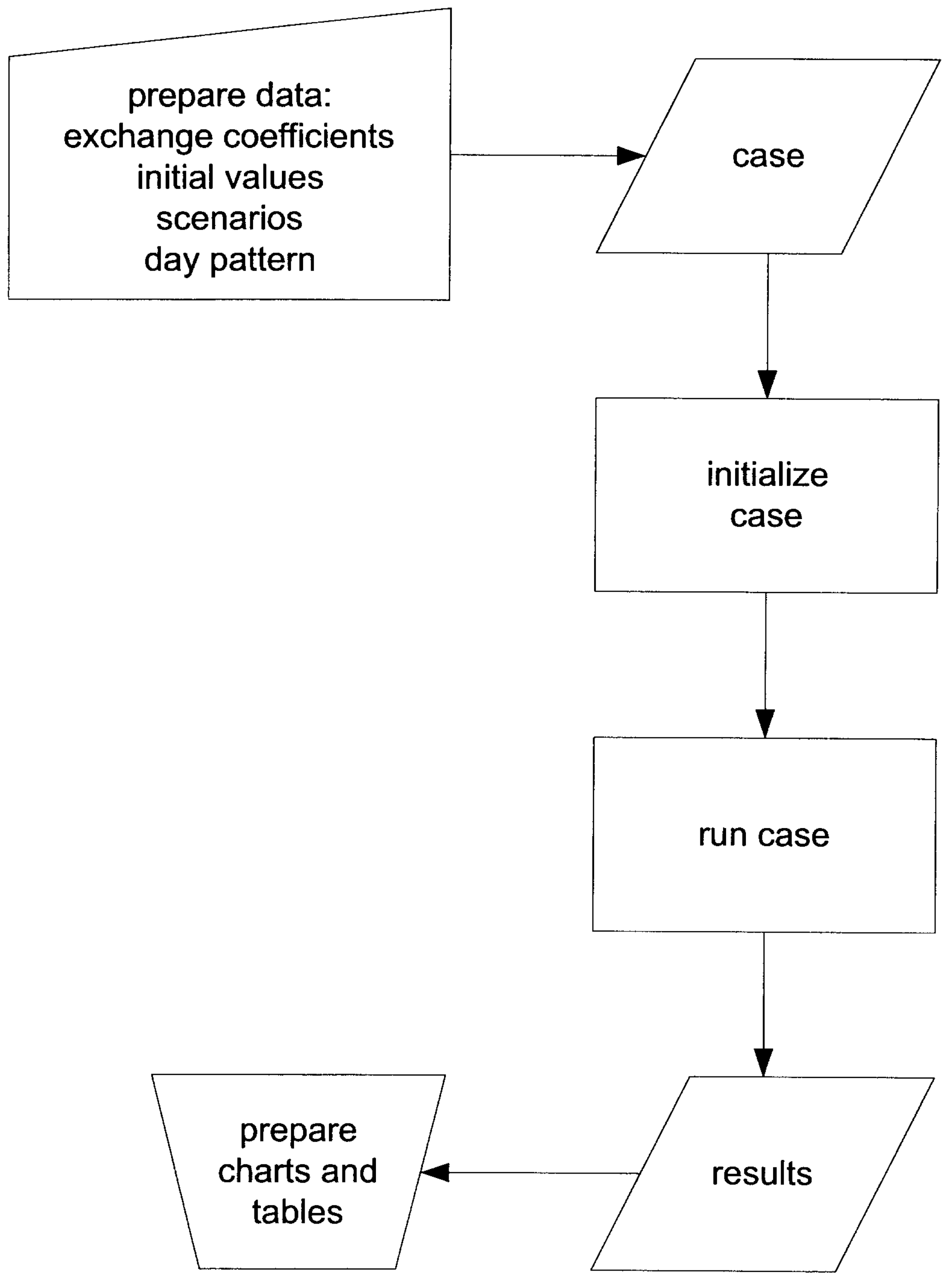


SIMULATION MODEL
COMPOSITION OF CASE

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.2

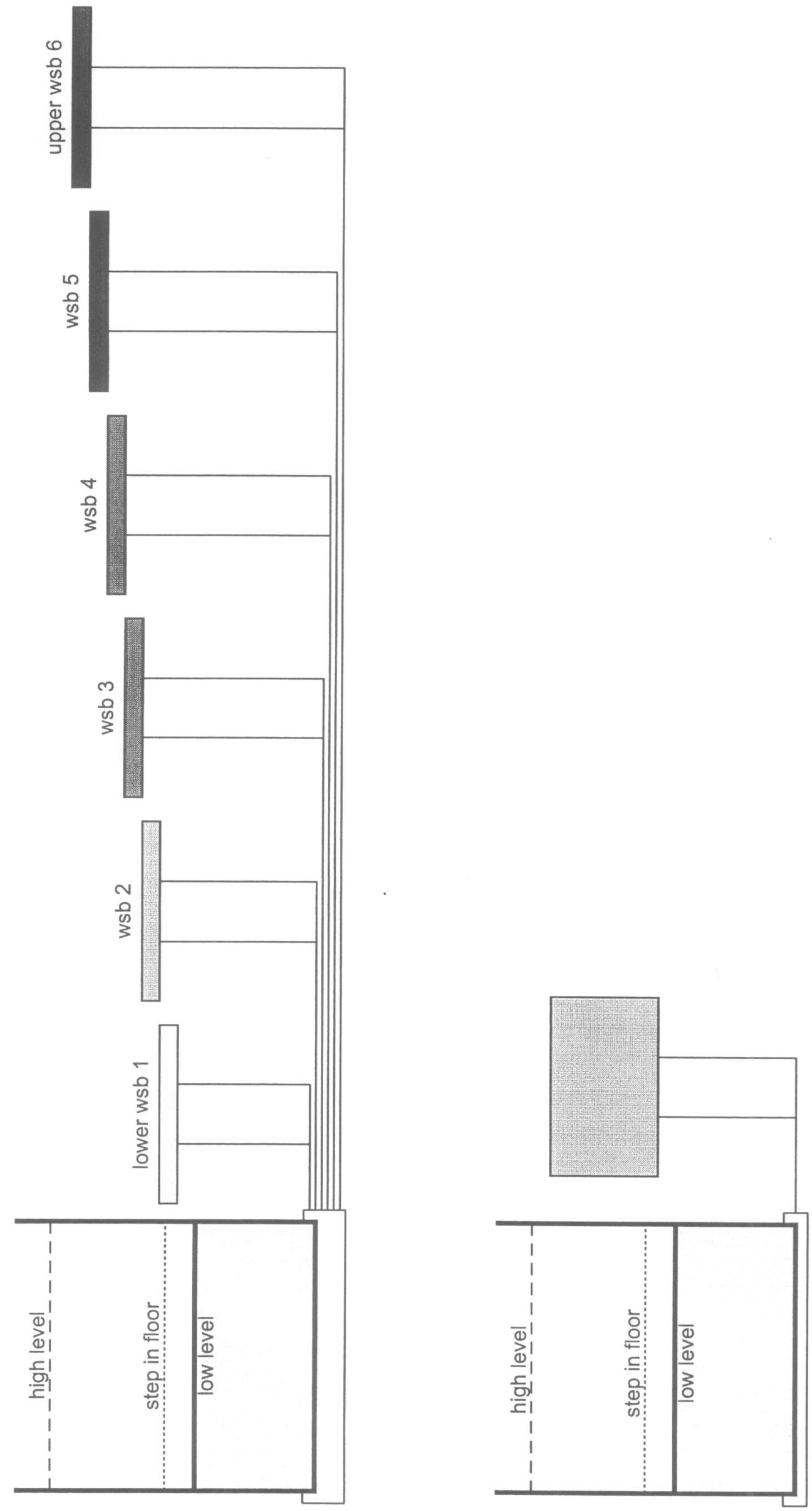


SIMULATION MODEL
FLOW CHART

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.3



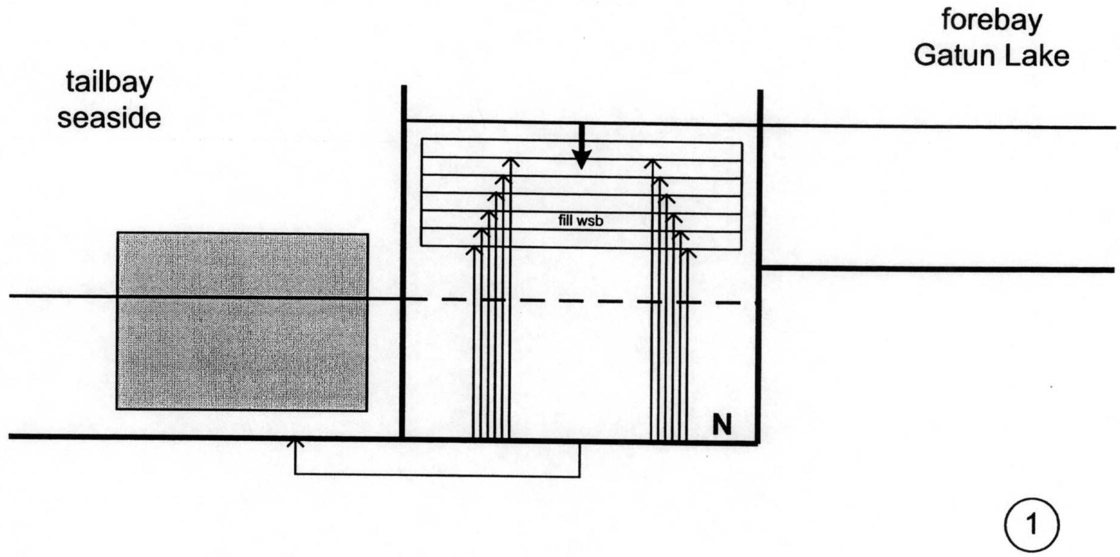
REPRESENTATION OF LOCK WITH 6 WSB'S
BY LOCK WITH SINGLE WSB

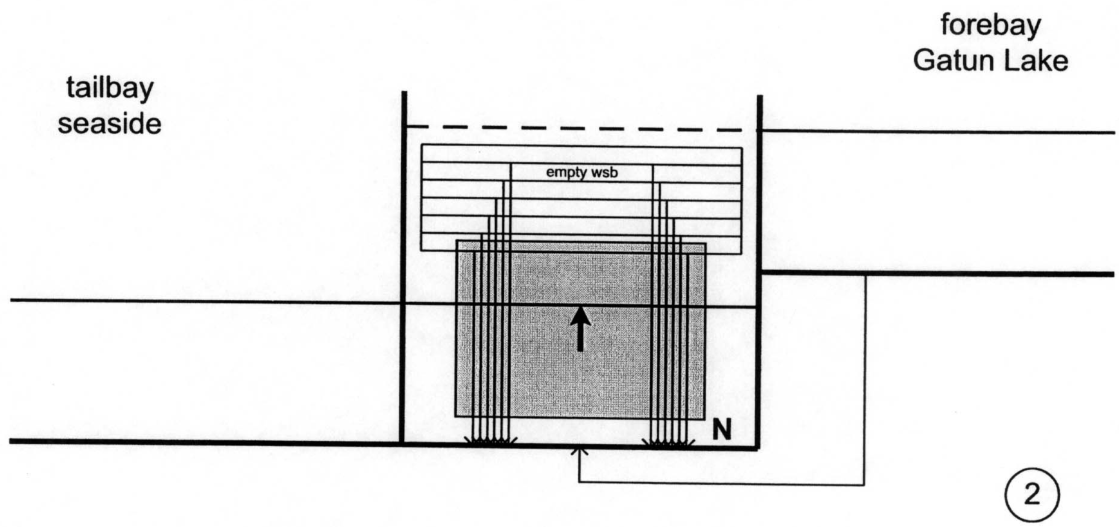
1-lift locks

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.4





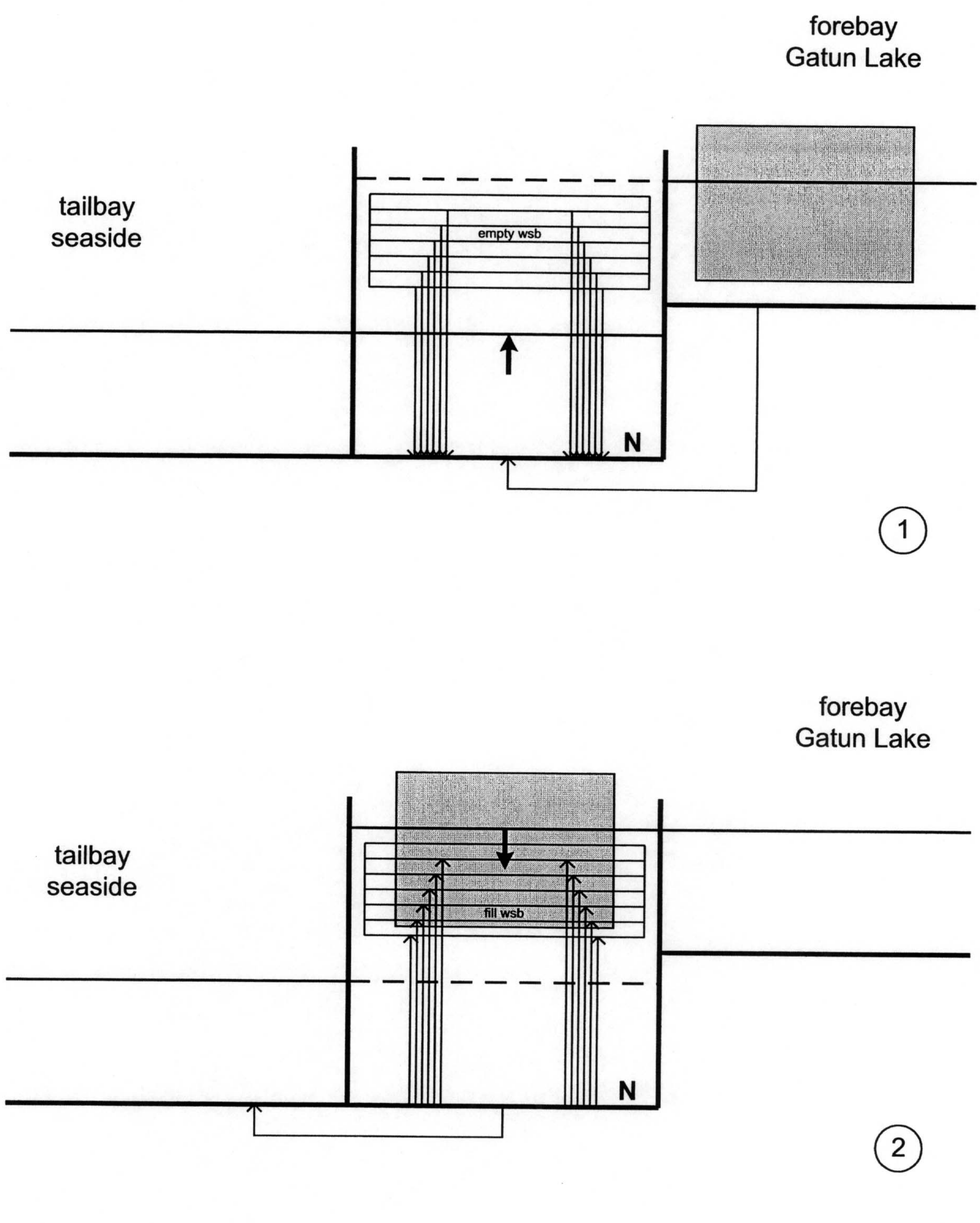
UPLOCKAGE
FILLING AND EMPTYING OF WSB'S IN STEP I

1-lift locks

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.5



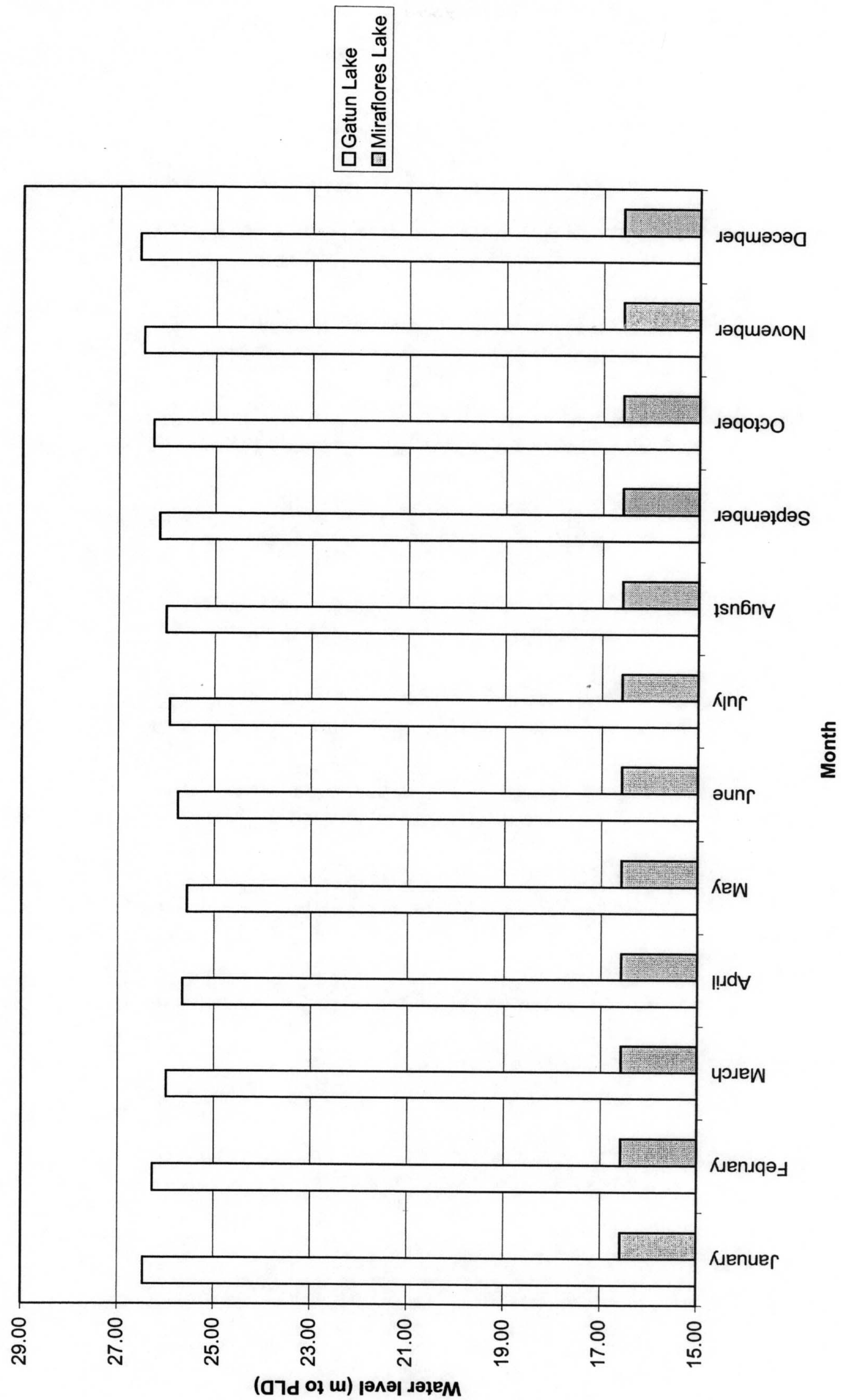
DOWNLOCKAGE
FILLING AND EMPTYING OF WSB'S IN STEP I

1-lift locks

WL | DELFT HYDRAULICS

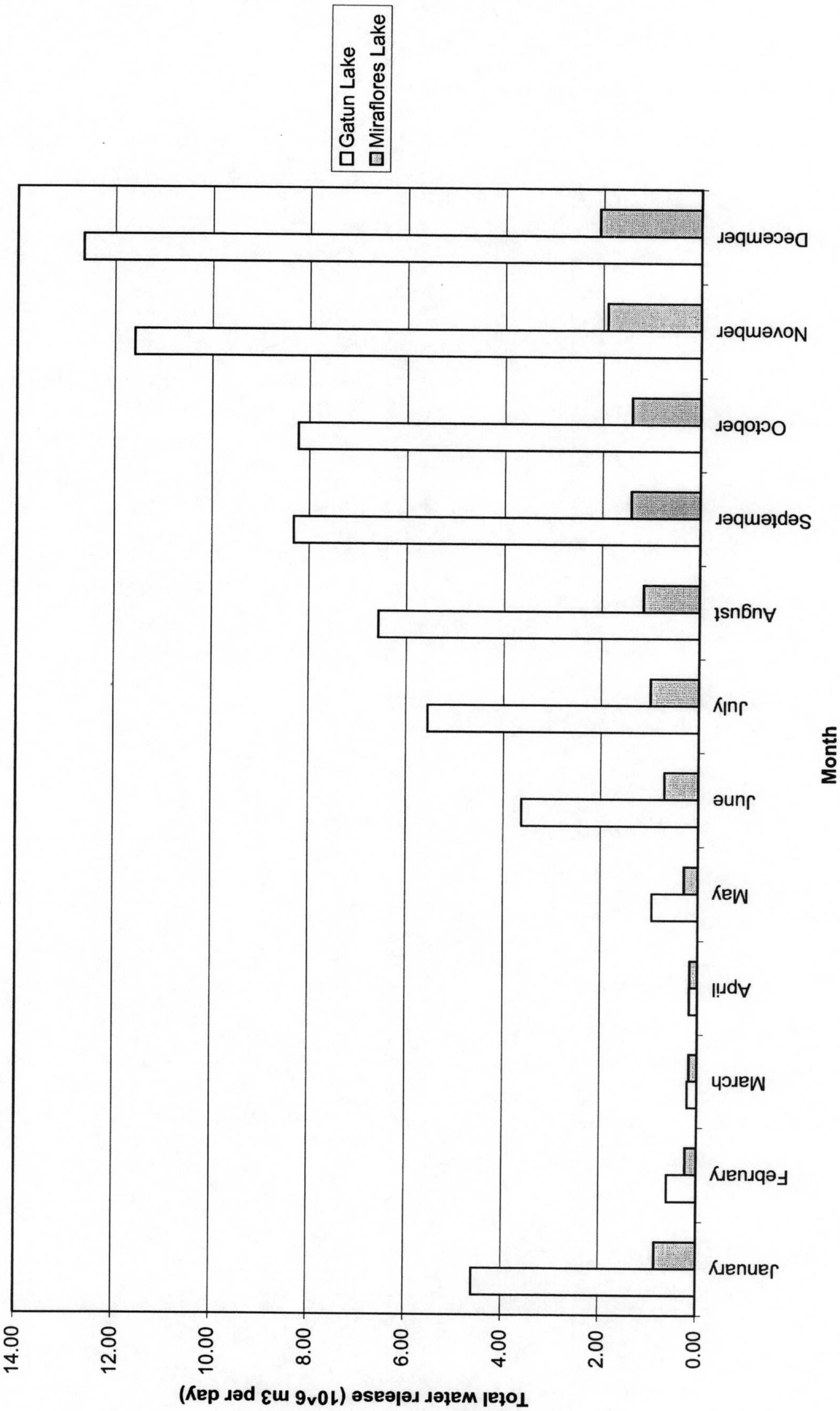
Q 3039

Fig. 3.6

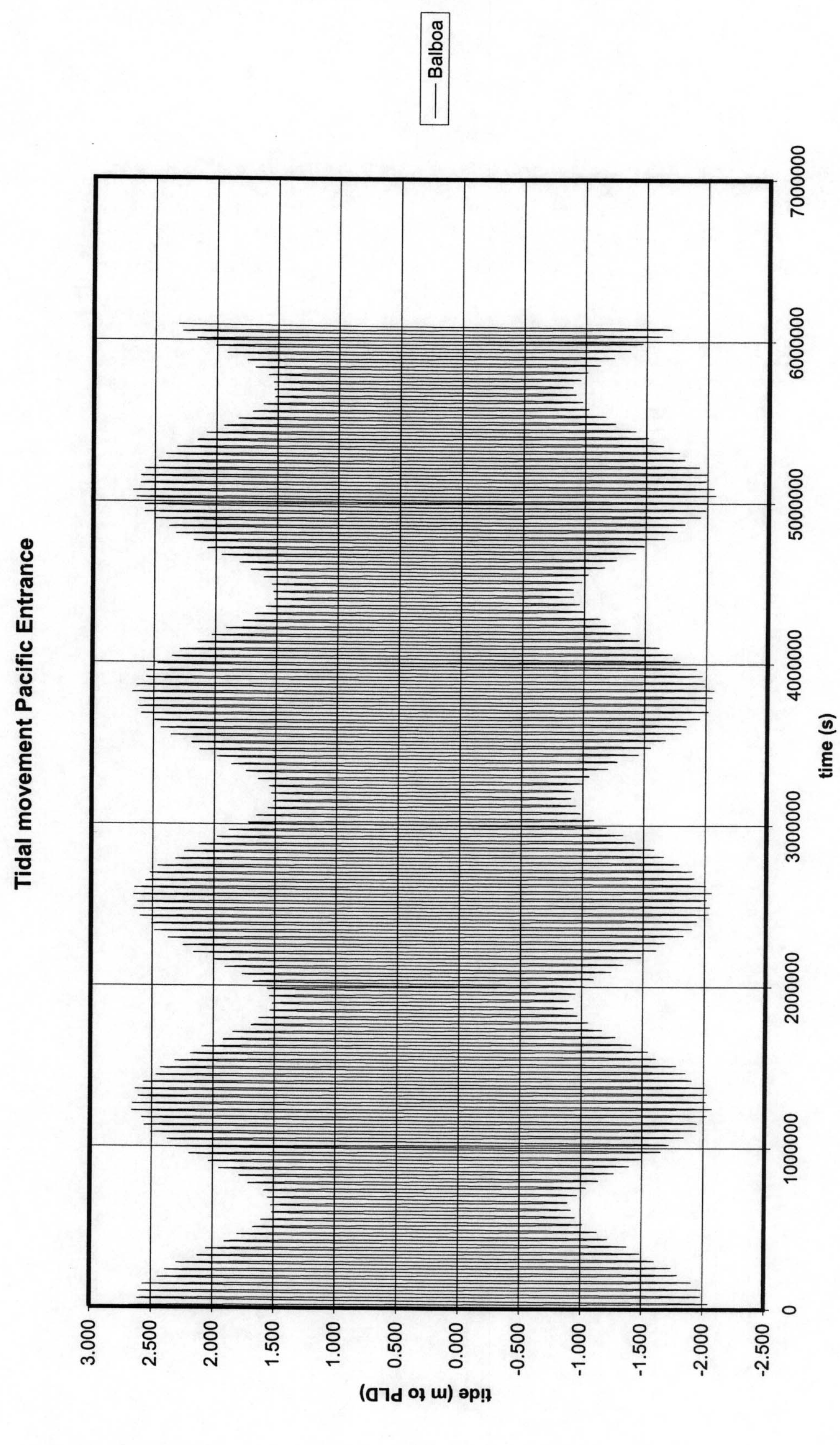


GATUN LAKE AND MIRAFLORES LAKE
REPRESENTATIVE WATER LEVELS

WL | DELFT HYDRAULICS	Q 3039	Fig. 3.7



GATUN LAKE AND MIRAFLORES LAKE WATER RELEASES (BASELINE SCENARIO)		
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.8

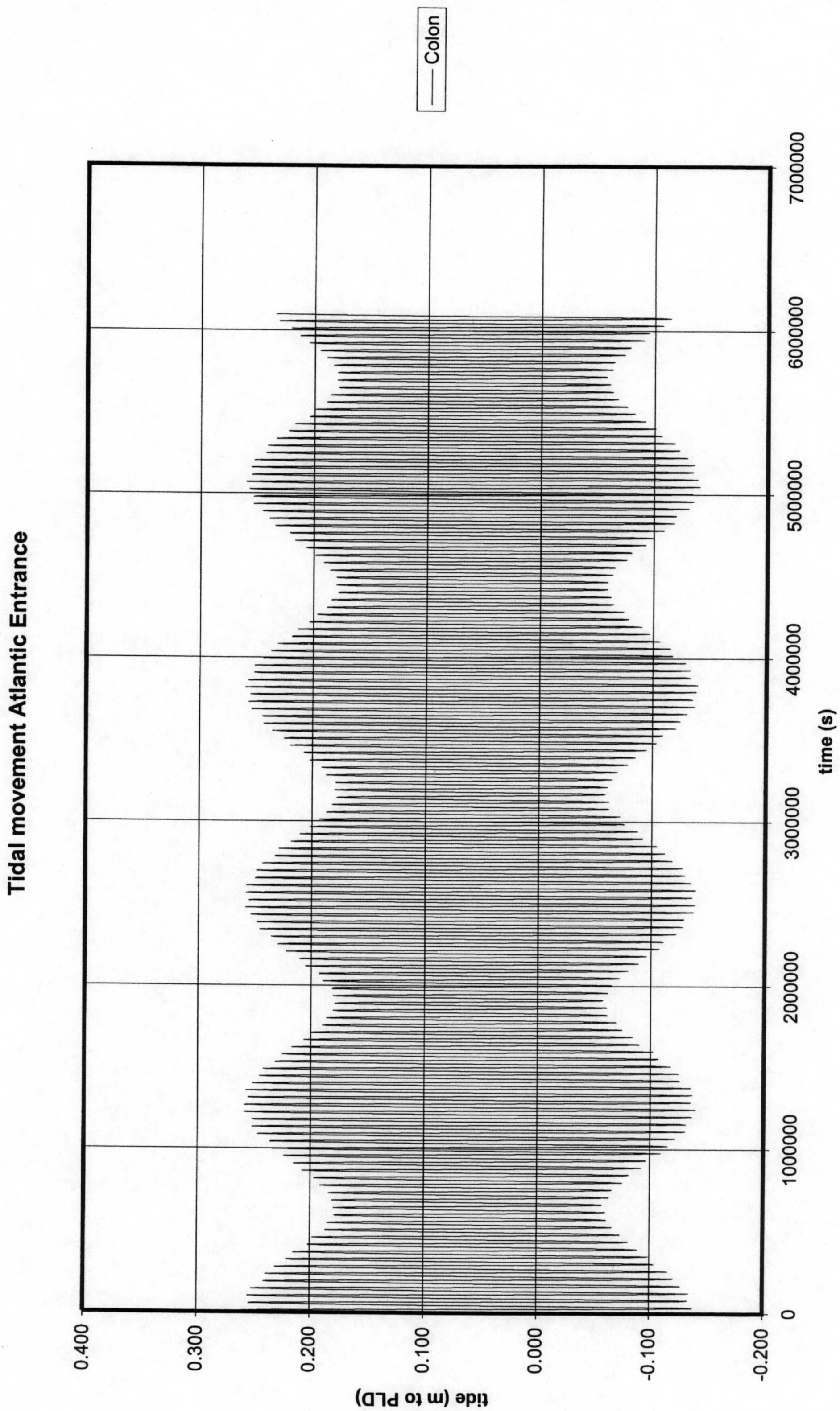


TAILBAYS PACIFIC SIDE
PREDICTION OF TIDAL MOVEMENT

WL | DELFT HYDRAULICS

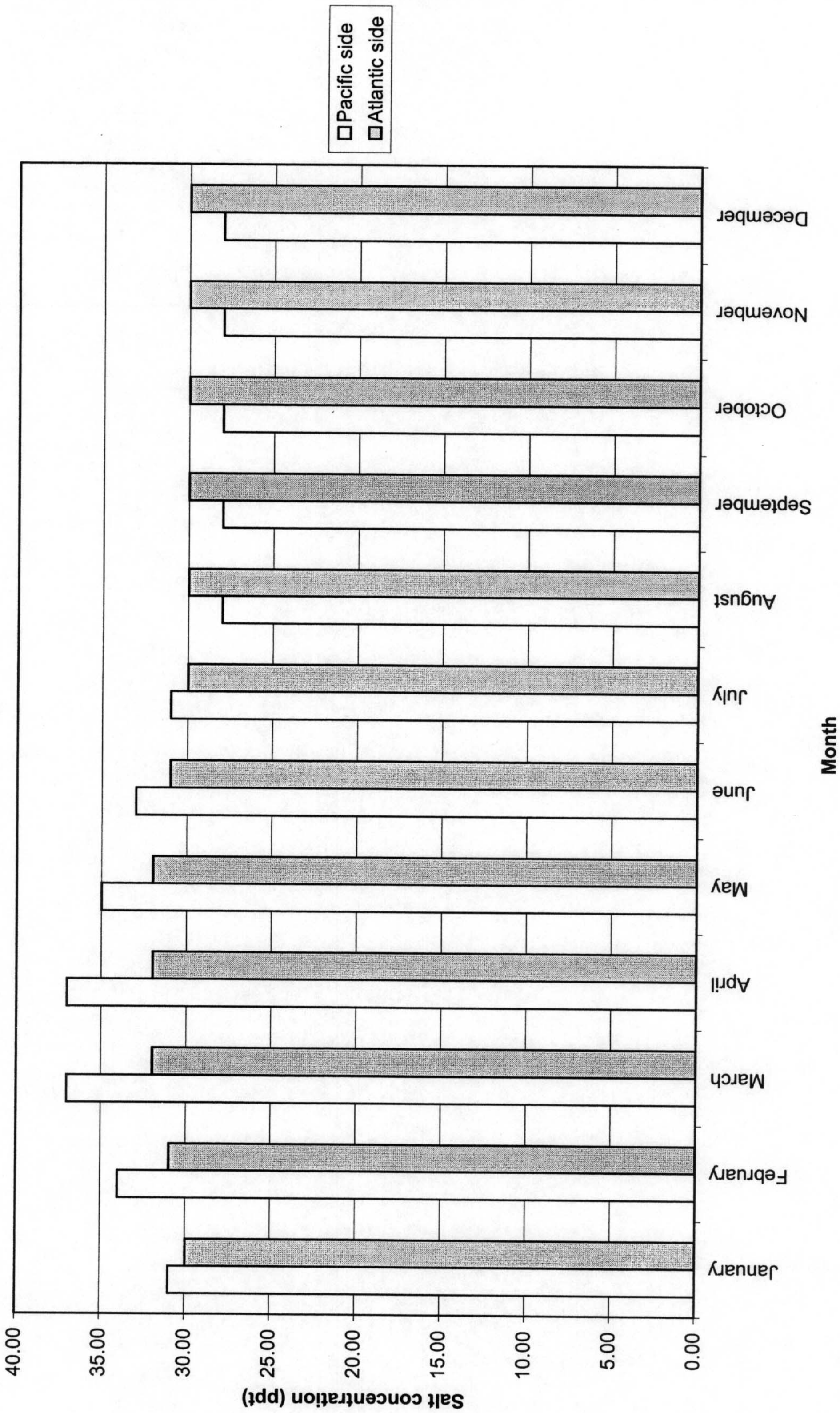
Q 3039

Fig. 3.9

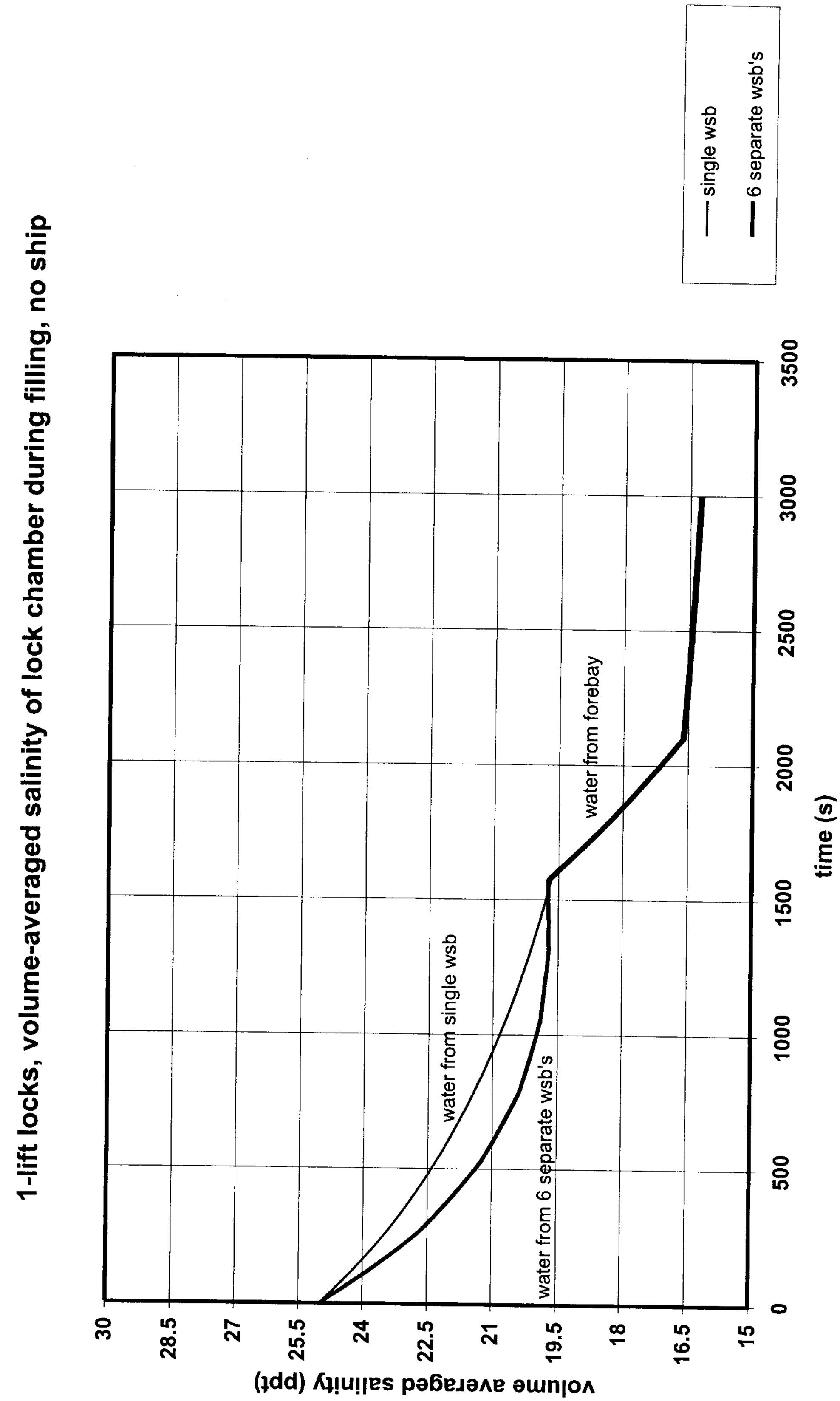


TAILBAYS ATLANTIC SIDE
PREDICTION OF TIDAL MOVEMENT

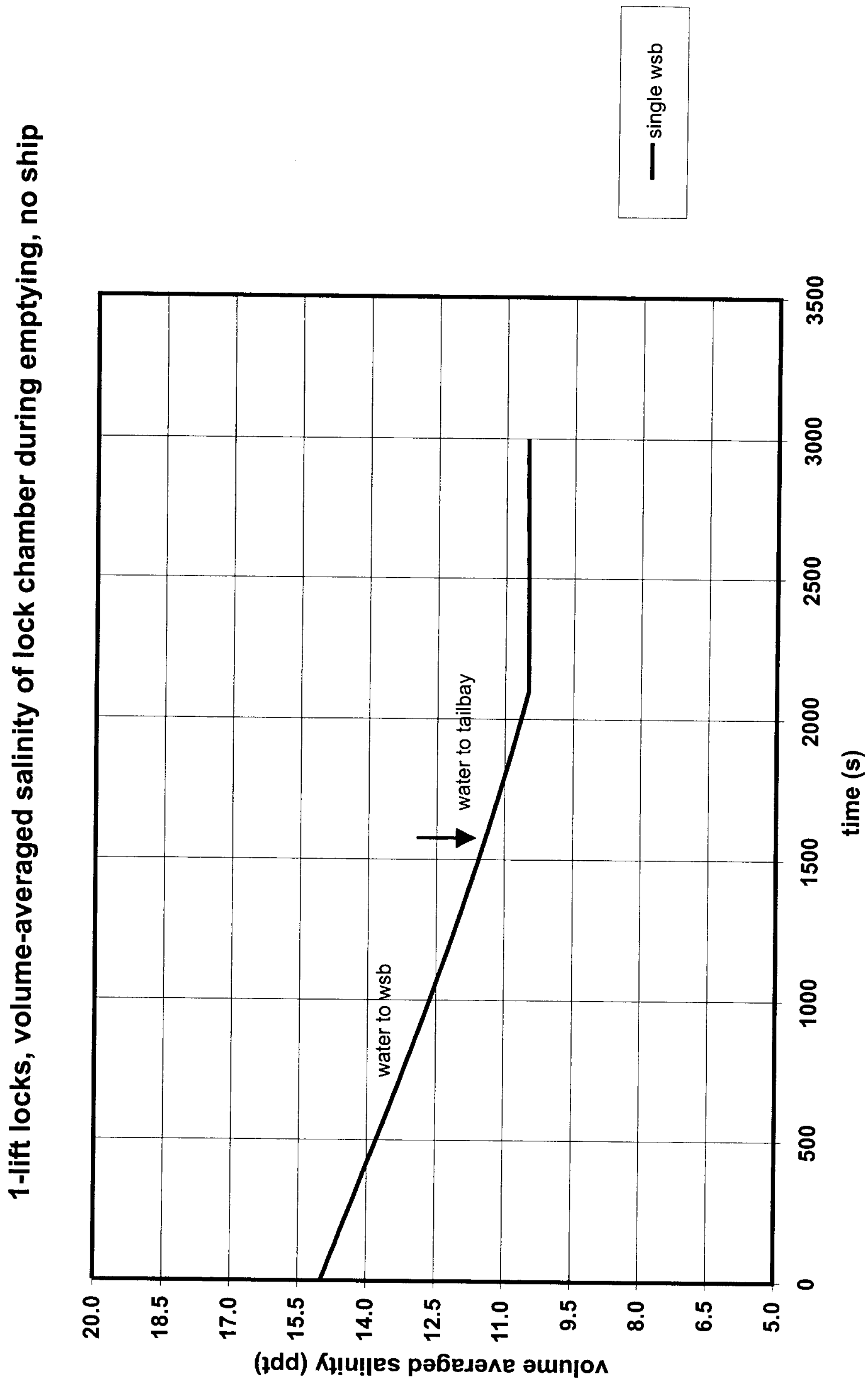
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.10



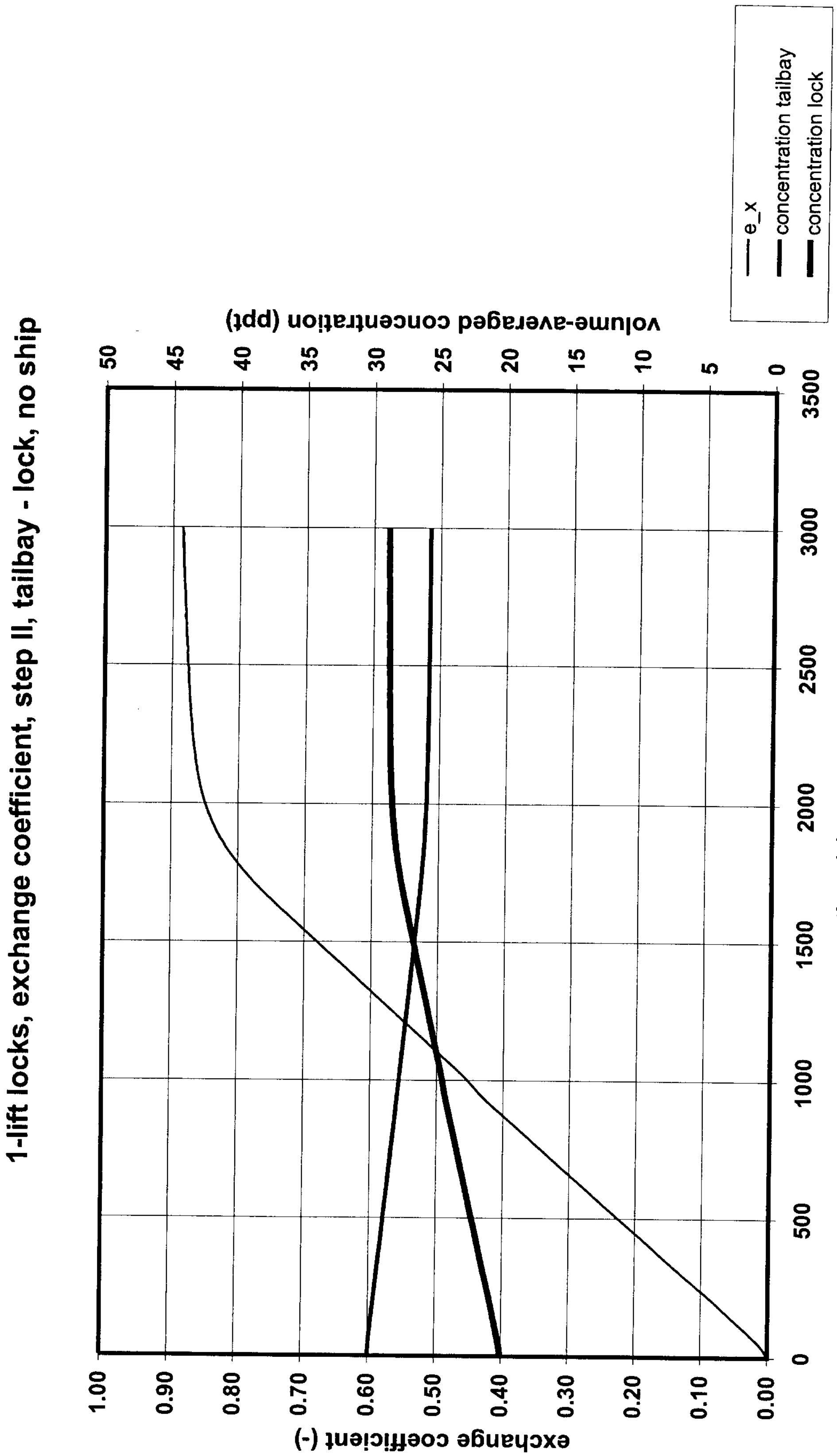
TEMPERATURE-COMPENSATED SALT CONCENTRATION OF PACIFIC AND ATLANTIC ENTRANCES		
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.11



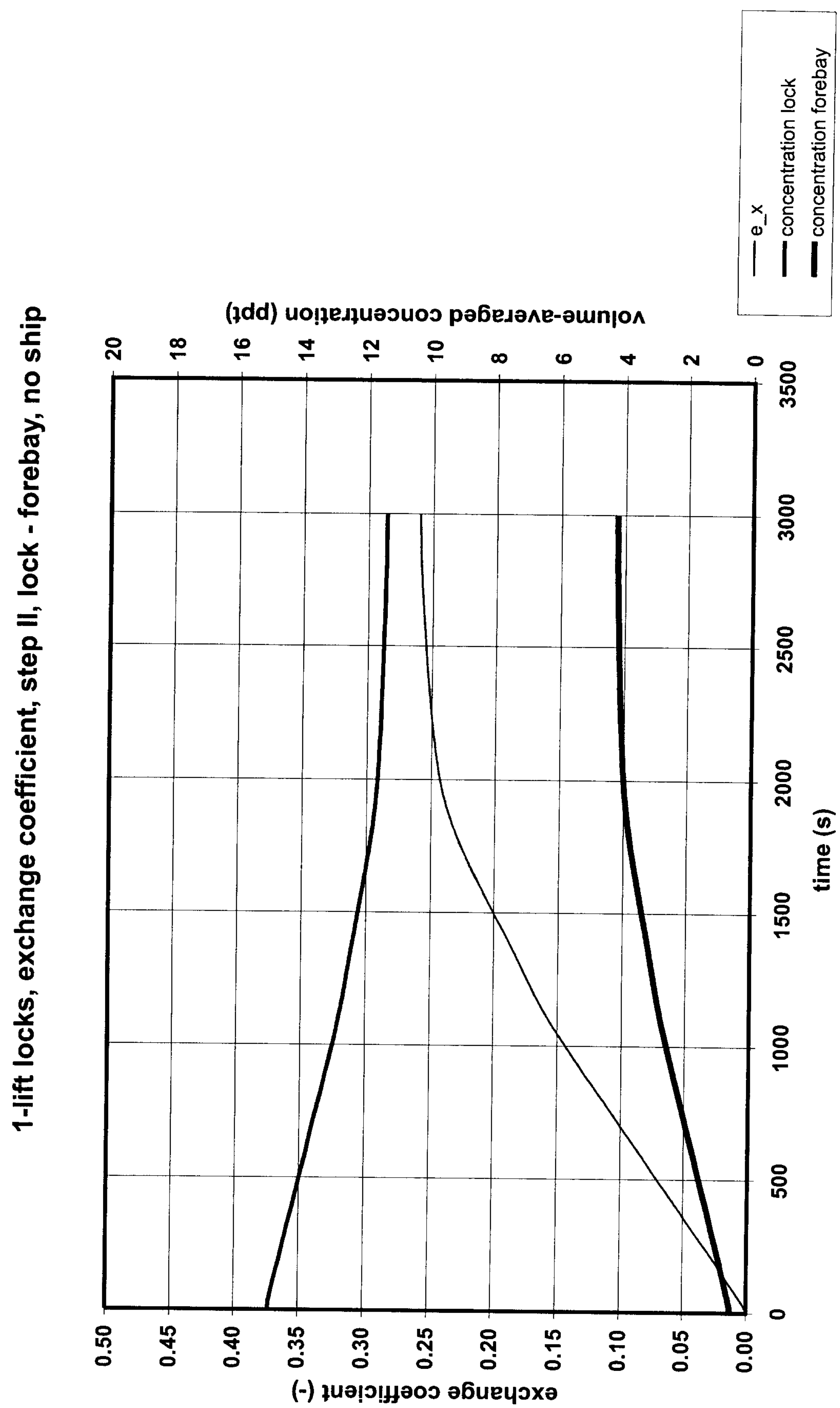
RESULTS OF DELFT3D COMPUTATION VOL-AVERAGED SALINITY OF LOCK, FILLING, NO SHIP	1-lift locks
WL | DELFT HYDRAULICS	Q 3039 | Fig. 5.1



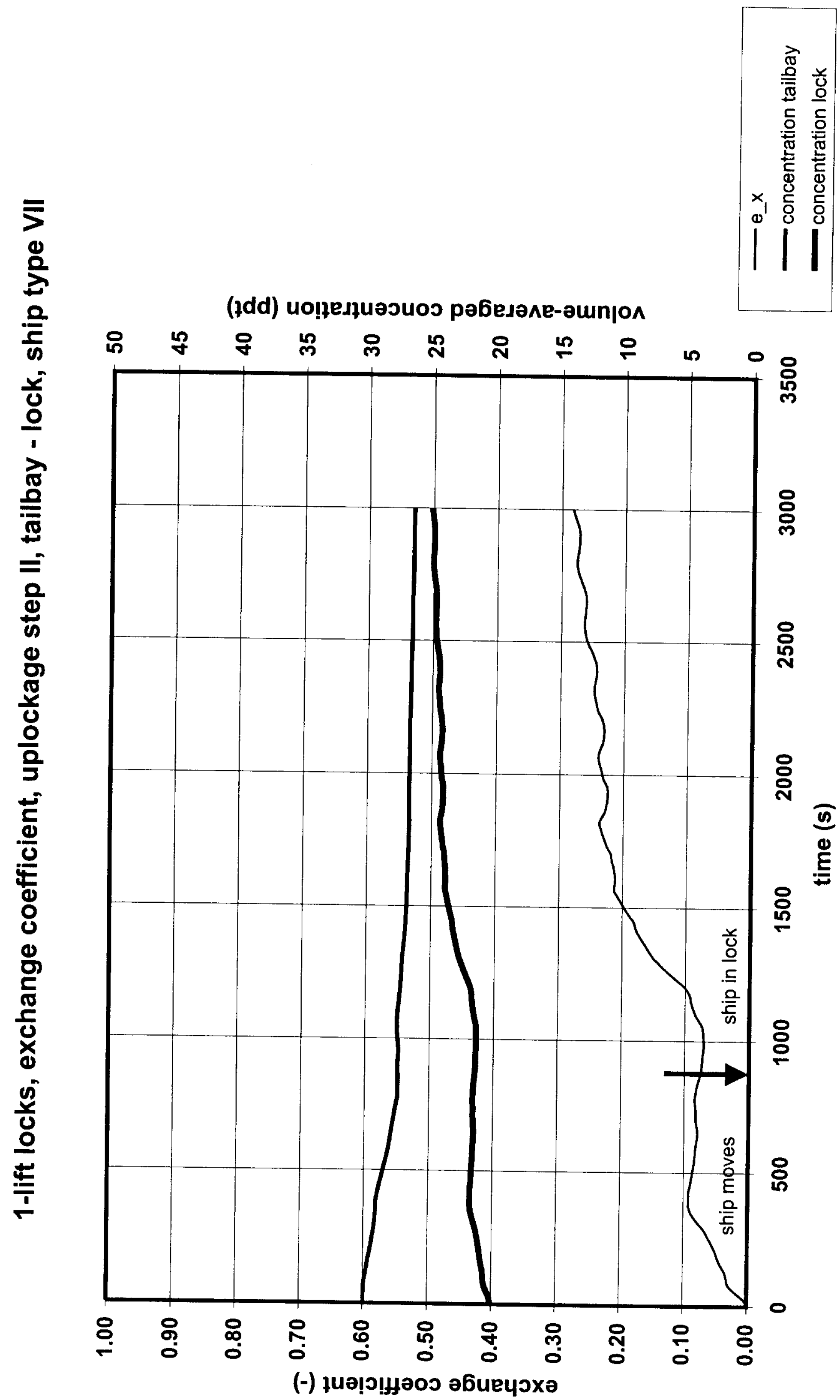
RESULTS OF DELFT3D COMPUTATION VOL-AVERAGED SALINITY OF LOCK, EMPTYING, NO SHIP	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.2



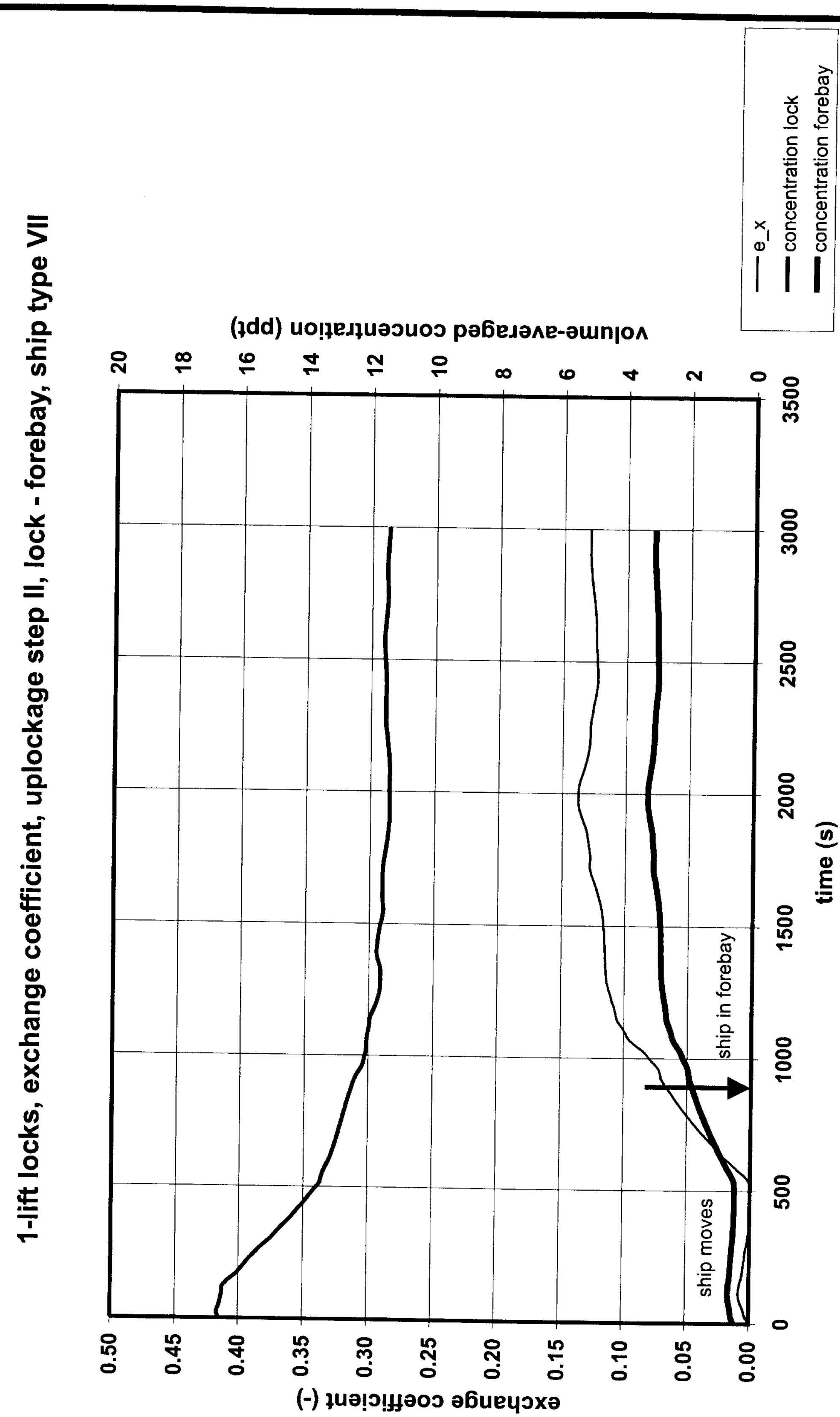
RESULTS OF DELFT3D COMPUTATION EXCHANGE COEFFICIENT, STEP II, TAILBAY - LOCK, NO SHIP	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.3a



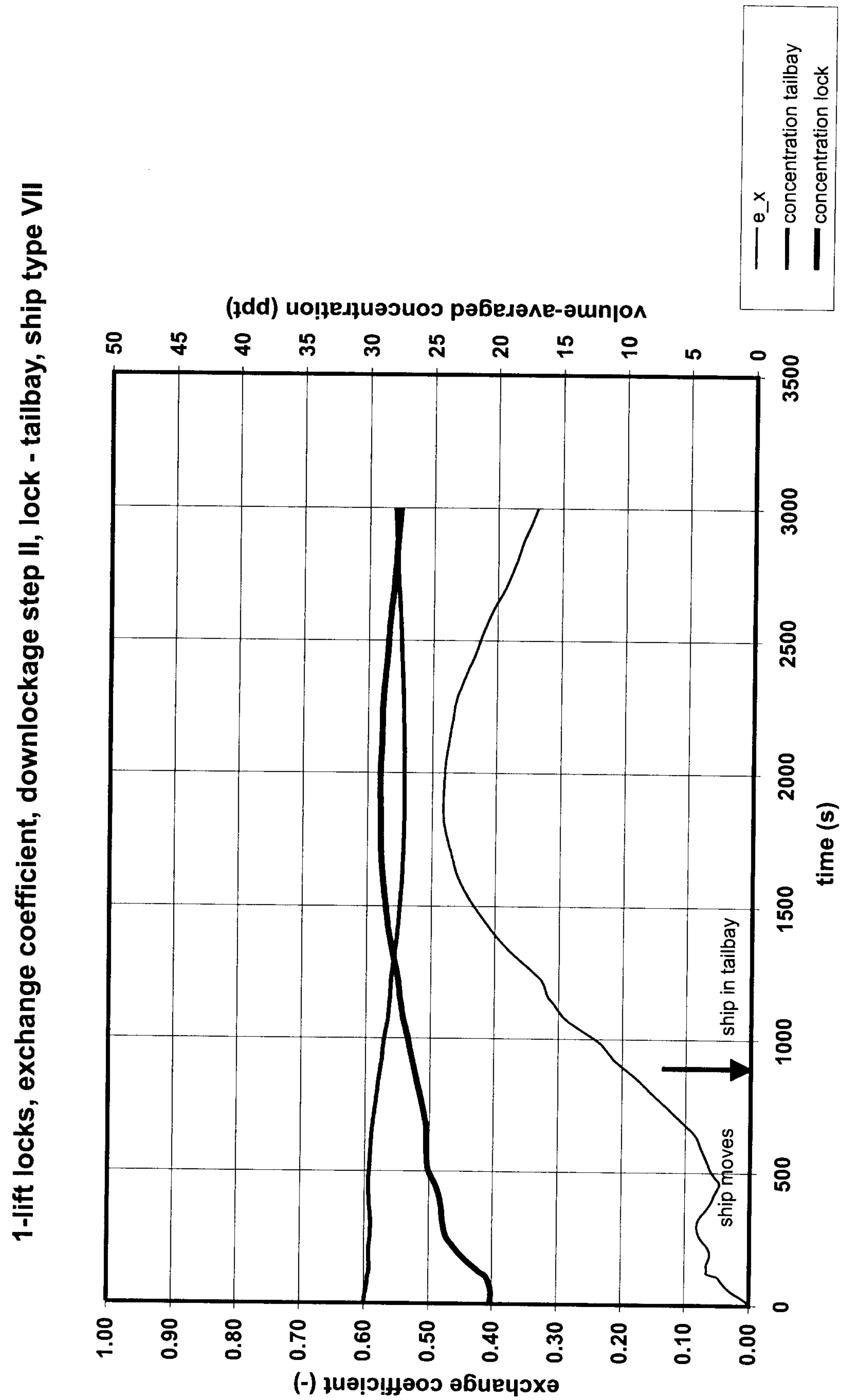
RESULTS OF DELFT3D COMPUTATION EXCHANGE COEFFICIENT, STEP II, LOCK - FOREBAY, NO SHIP		
	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.3b



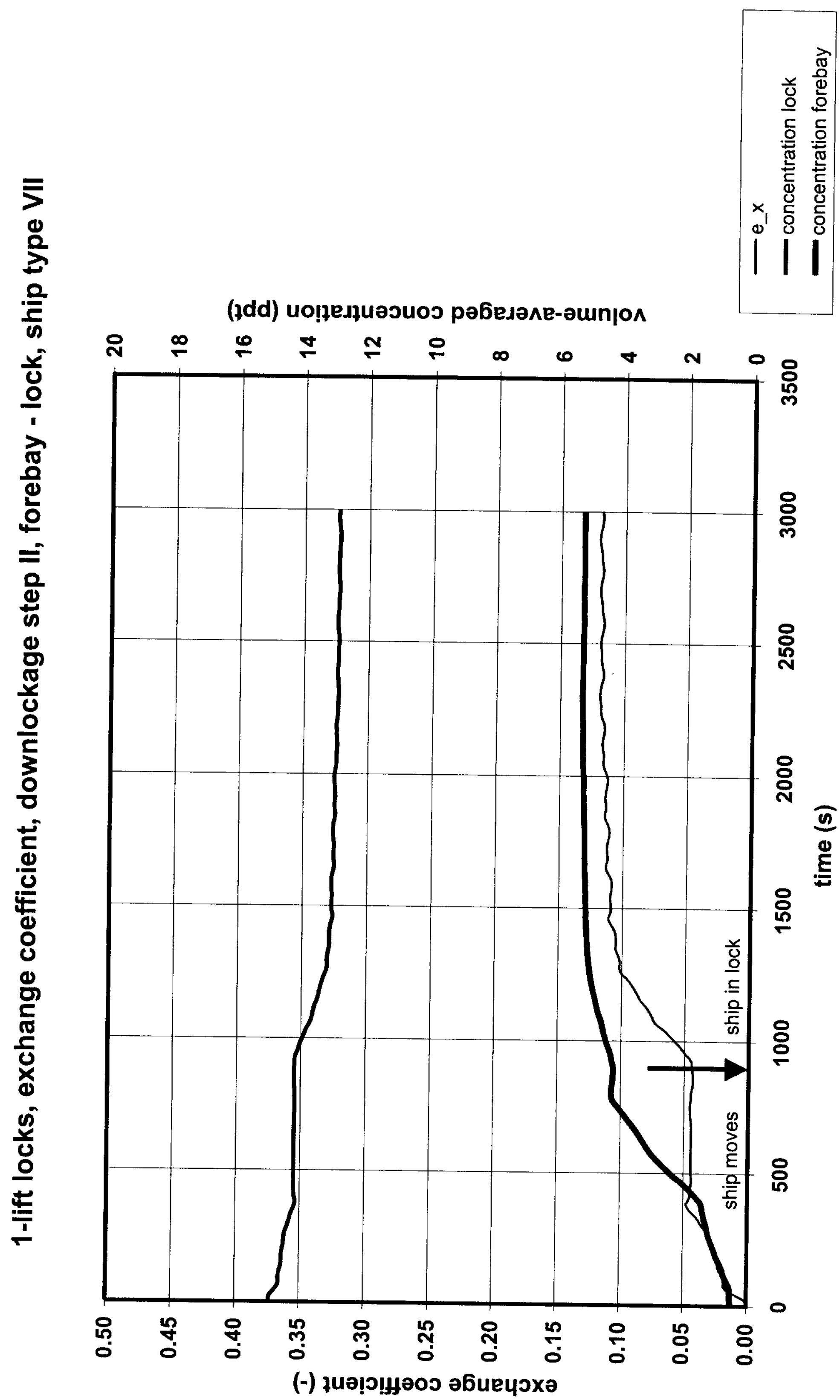
RESULTS OF DELFT3D COMPUTATION, EXCHANGE COEFF., UPLOCKAGE STEP II, TAILBAY - LOCK, SHIP TYPE VII		
	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.4a



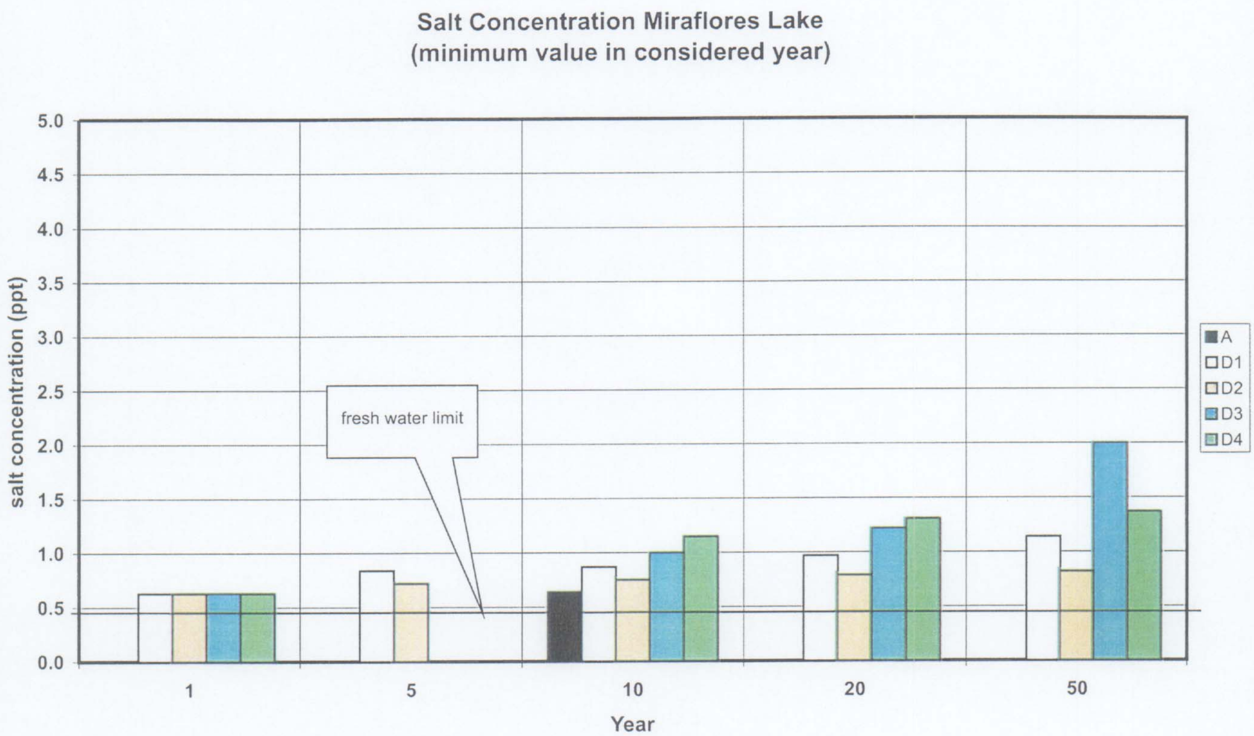
RESULTS OF DELFT3D COMPUTATION, EXCHANGE COEFF., UPLOCKAGE STEP II, LOCK - FOREBAY, SHIP TYPE VII		
	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.4b

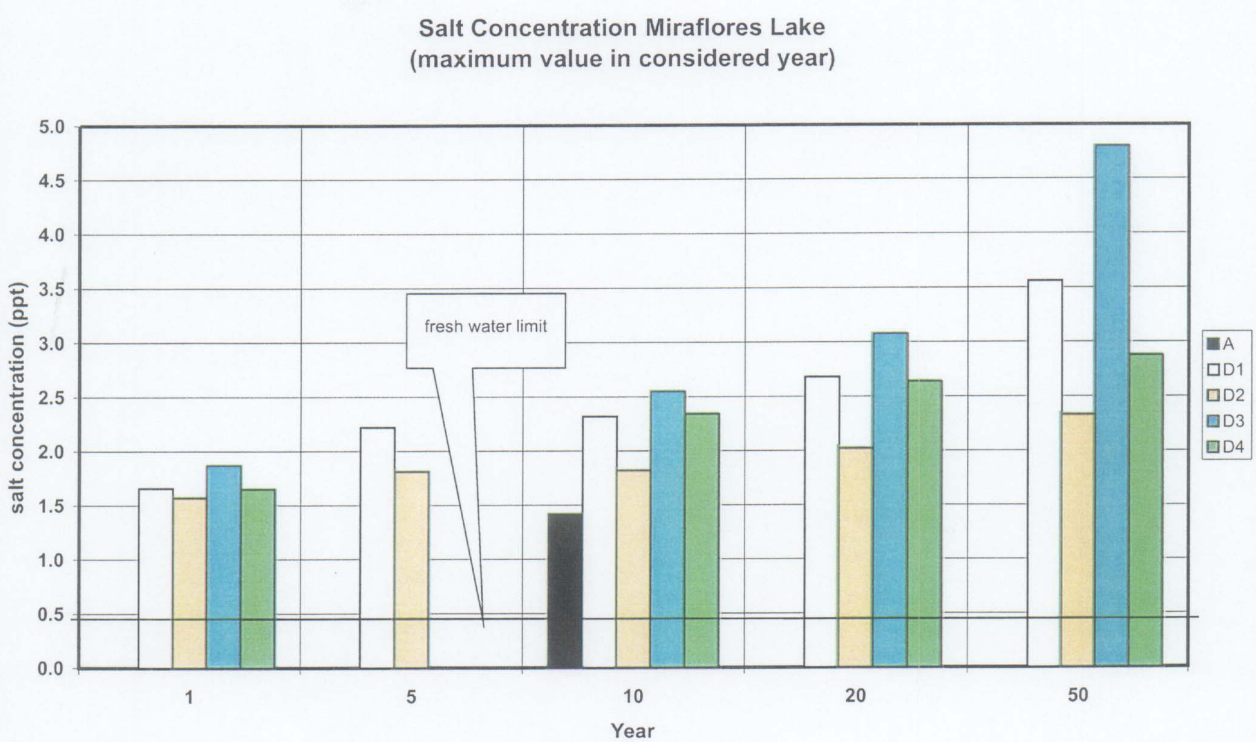


RESULTS OF DELFT3D COMPUTATION, EXCHANGE COEFF., DOWNLOCKAGE STEP II, LOCK - TAILBAY, SHIP TYPE VII	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.5a

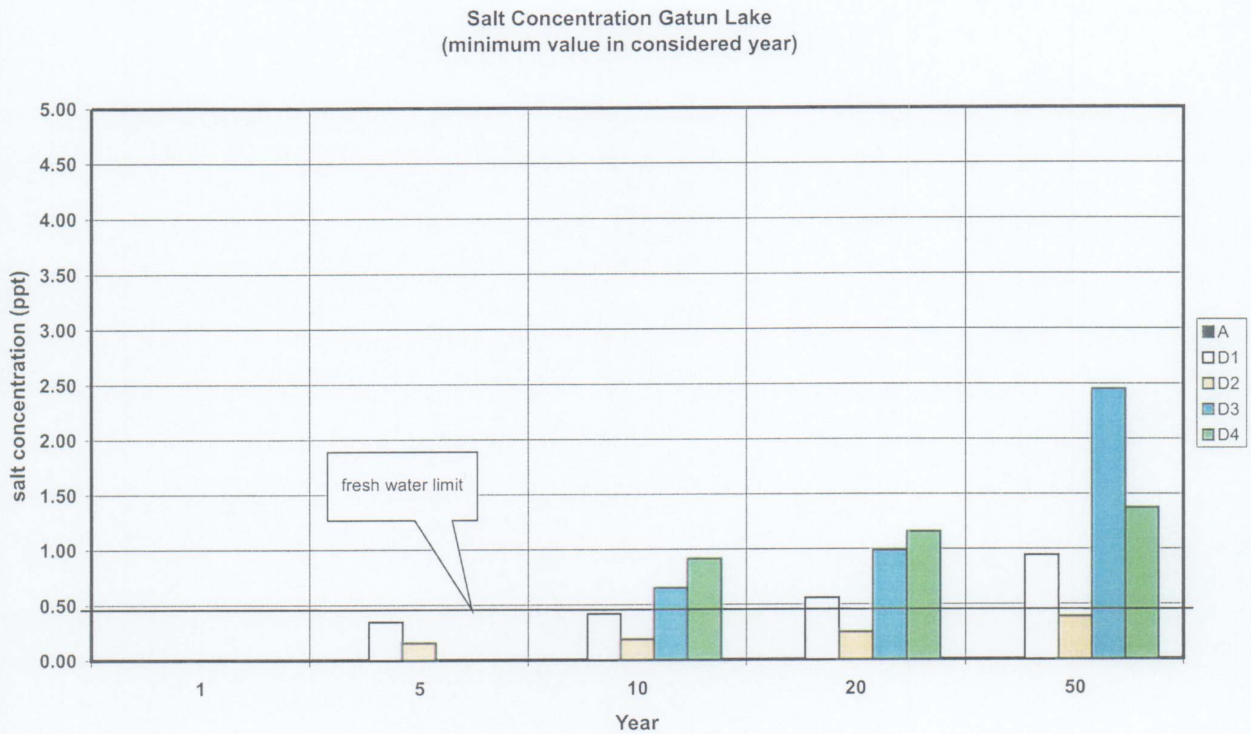


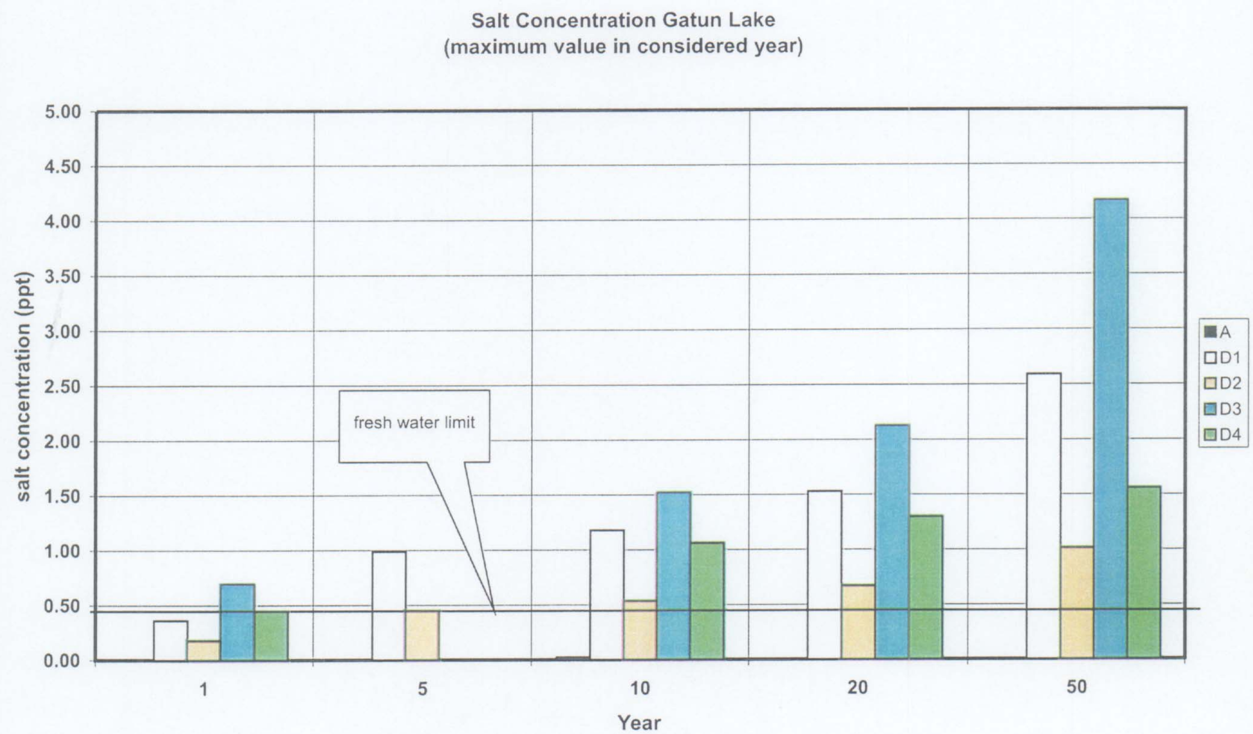
RESULTS OF DELFT3D COMPUTATION, EXCHANGE COEFF., DOWNLOCKAGE STEP II, FOREBAY - LOCK, SHIP TYPE VII	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.5b



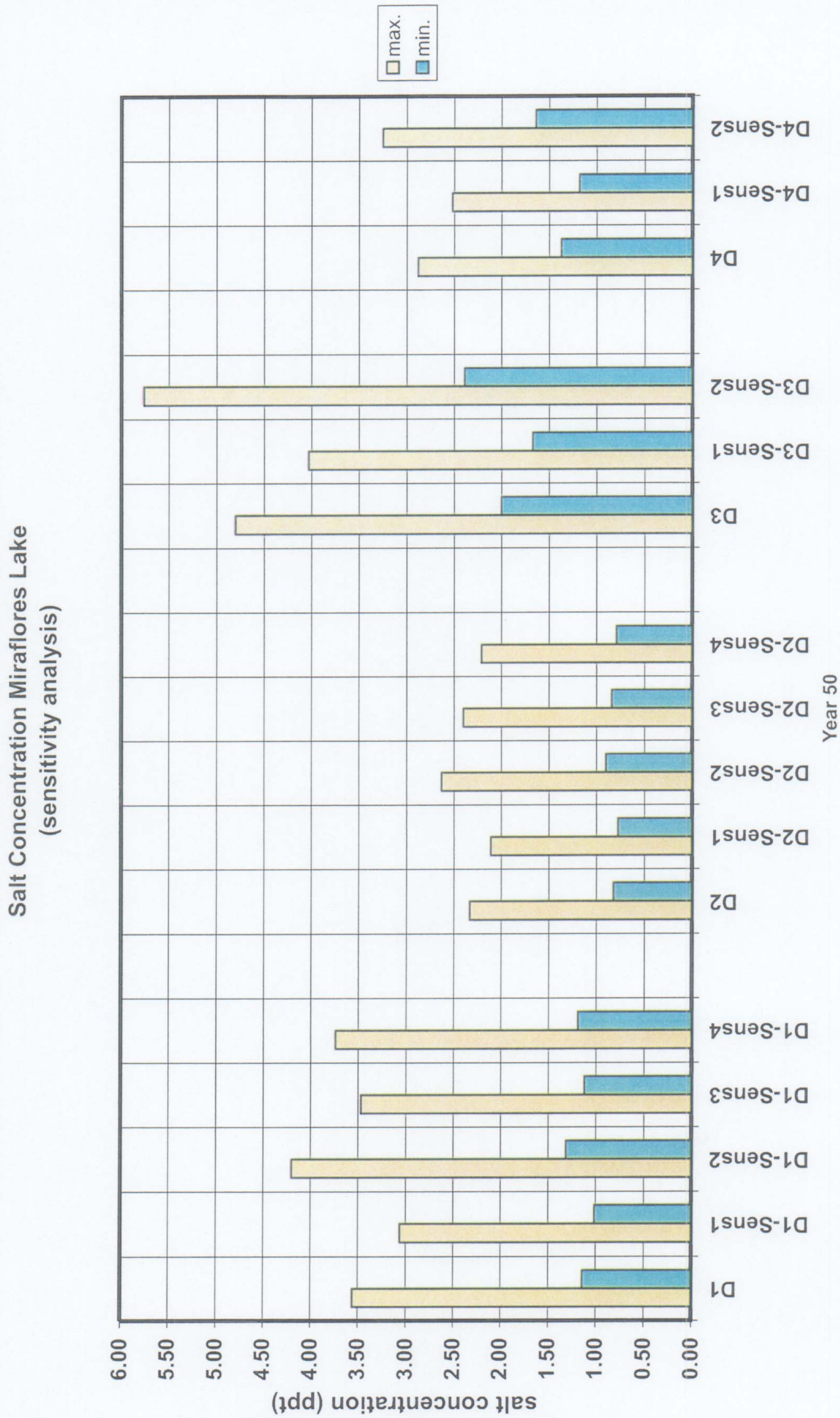


SALT CONCENTRATION MIRAFLORES LAKE maximum and minimum value in considered year	1-lift locks
WL | DELFT HYDRAULICS	Q 3039 | Fig. 7.1

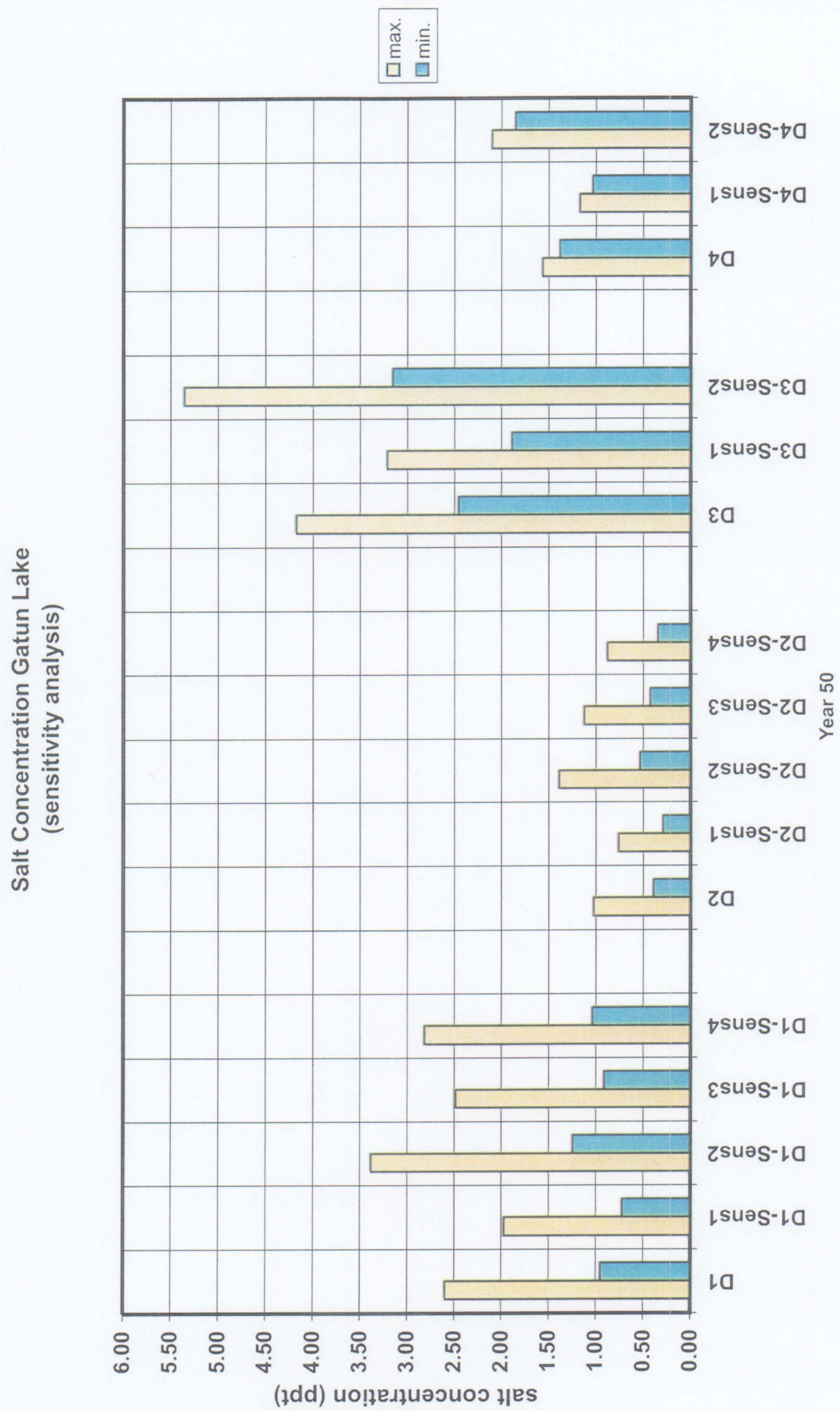




SALT CONCENTRATION GATUN LAKE maximum and minimum value in considered year	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 7.2



SALT CONCENTRATION MIRAFLORES LAKE, YEAR 50 sensitivity analysis, various scenarios		
	1-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 7.3



SALT CONCENTRATION GATUN LAKE, YEAR 50
sensitivity analysis, various scenarios

1-lift locks	
Q 3039	Fig. 7.4

WL | DELFT HYDRAULICS

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Figure A-10, 1 Case A-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

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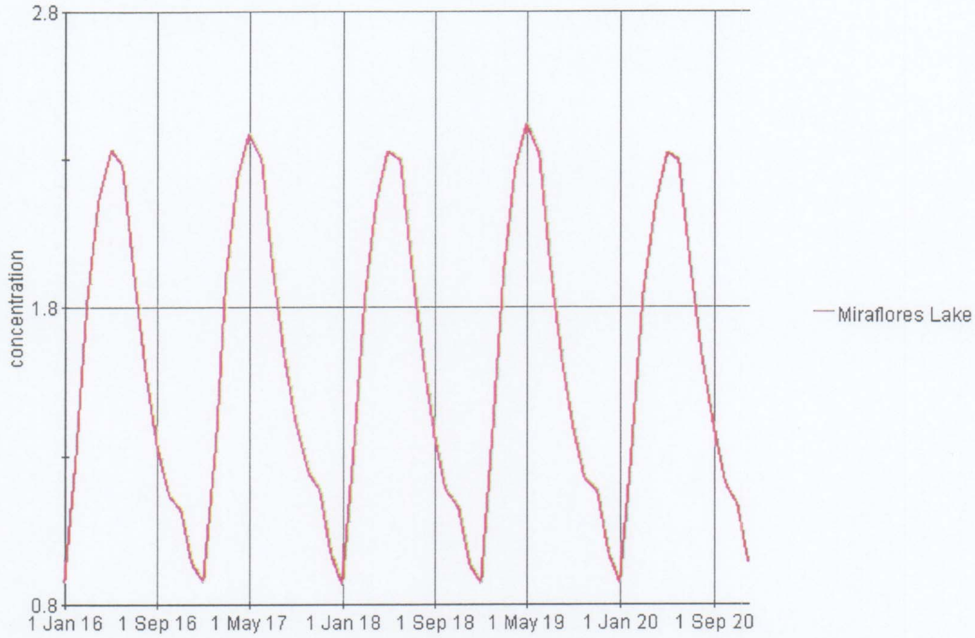

Figure D1-10, 1 Case D1-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

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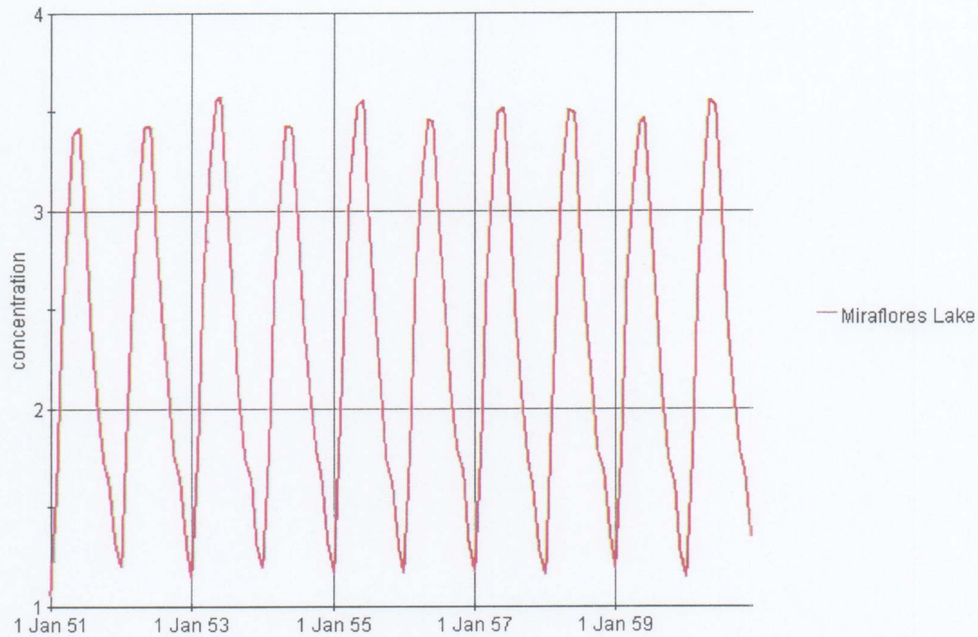
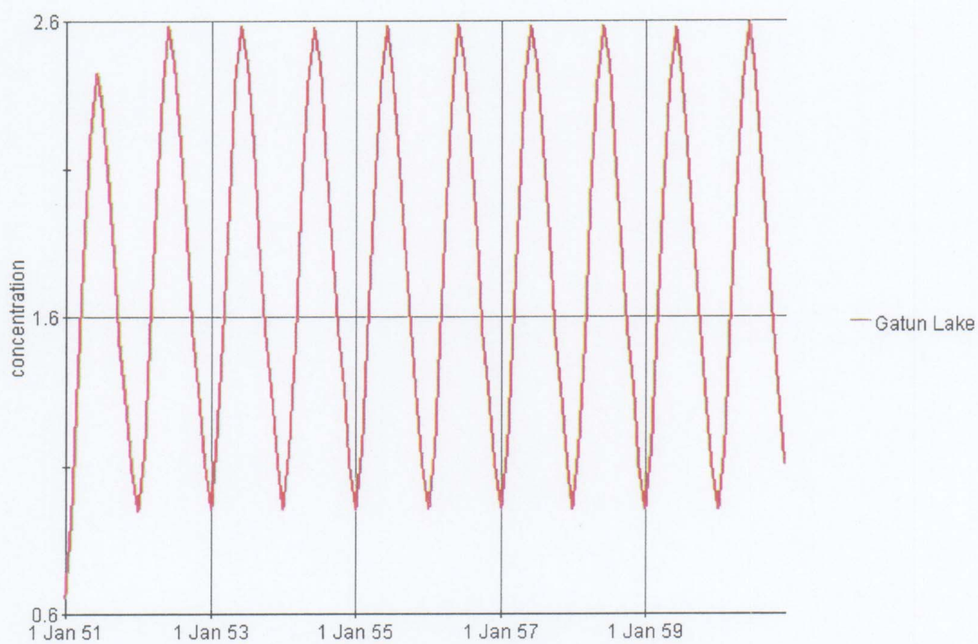


Figure D1-50, 1 Case D1-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)



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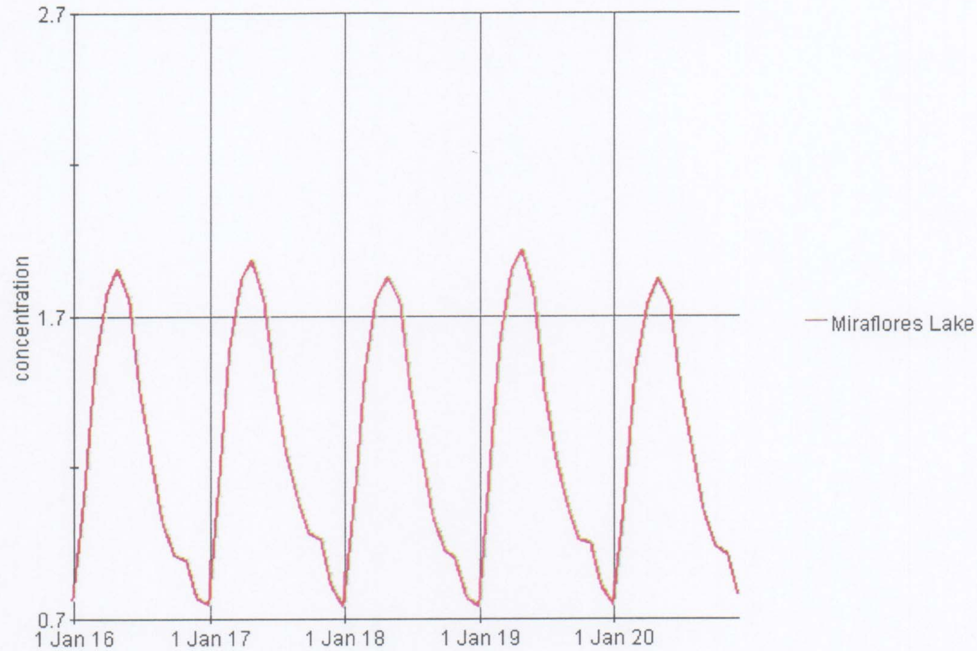
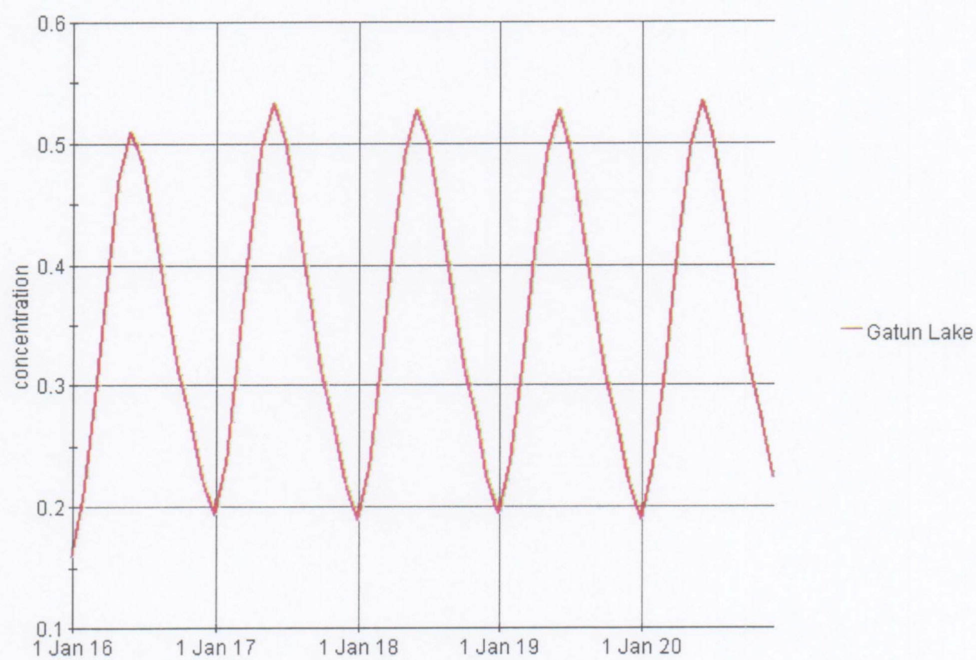


Figure D2-10, 1 Case D2-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)



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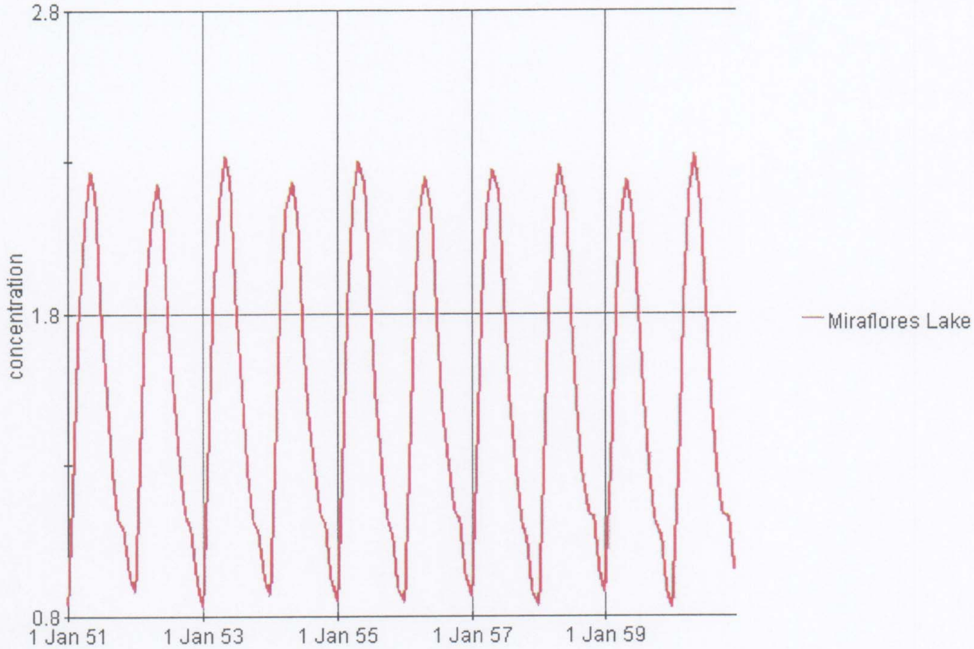


Figure D2-50, 1 Case D2-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

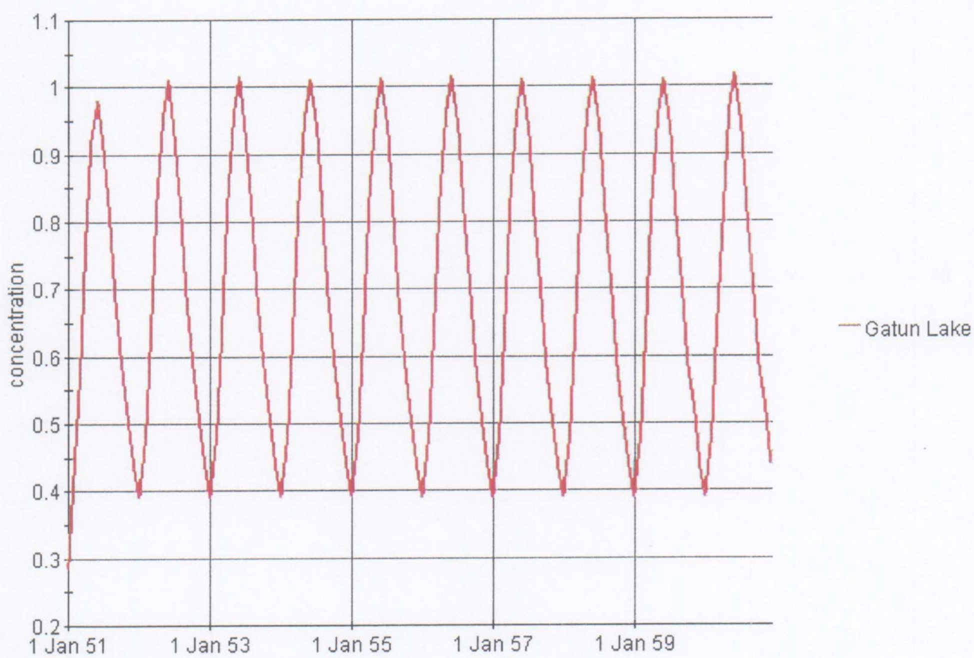


Figure D2-50, 2 Case D2-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

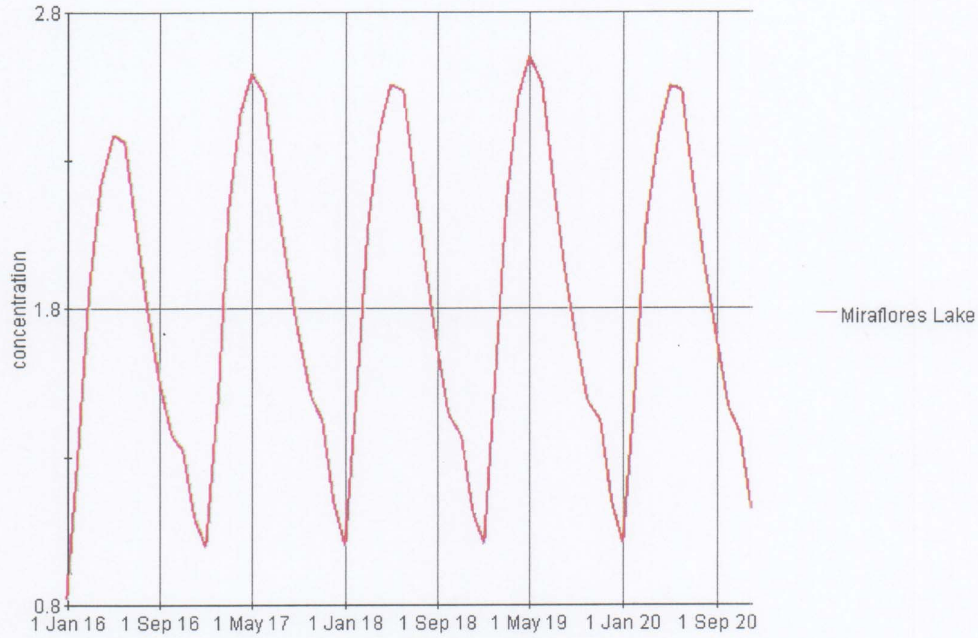
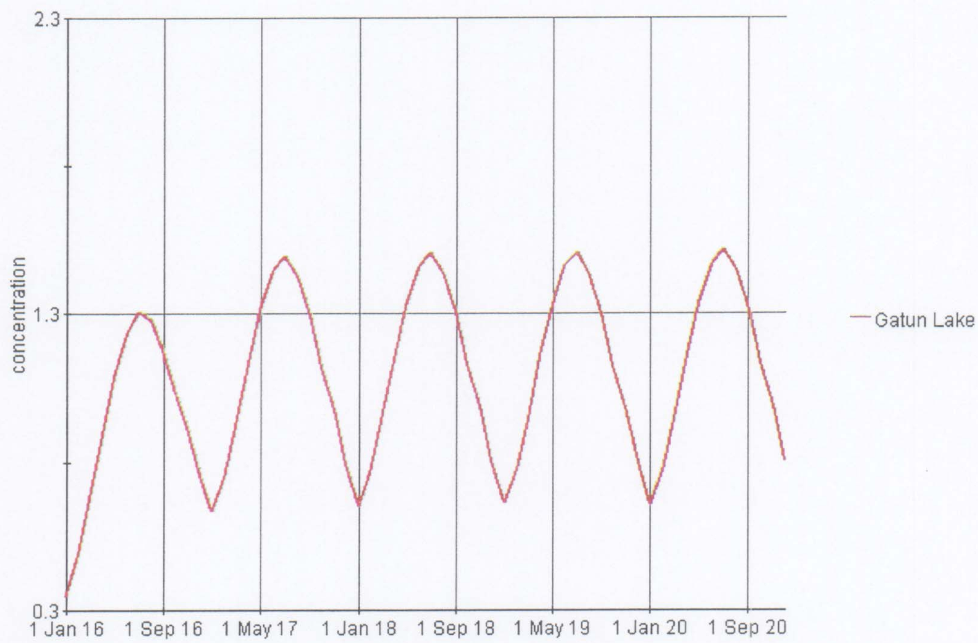


Figure D3-10, 1 Case D3-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)



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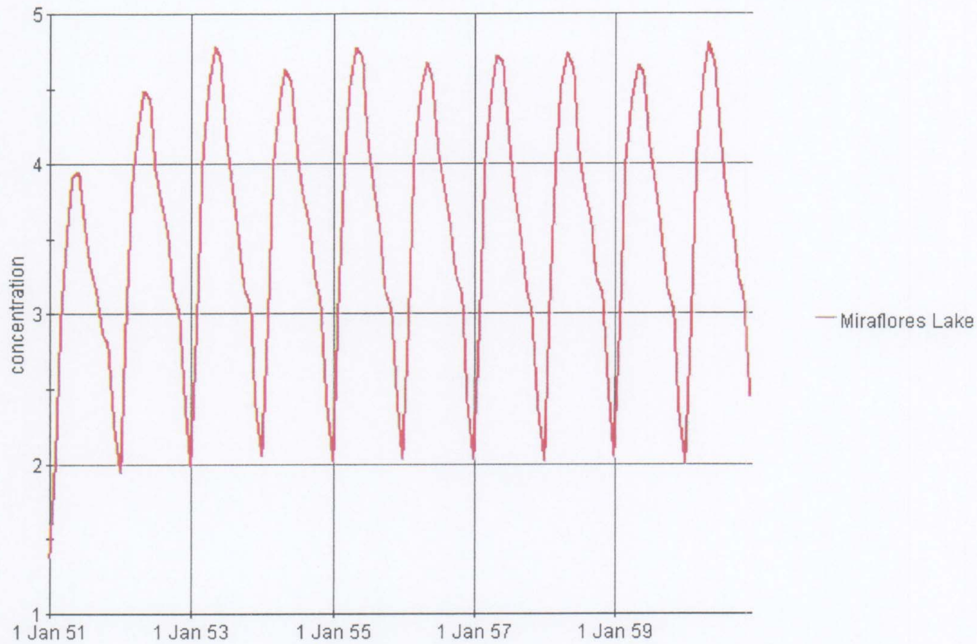


Figure D3-50, 1 Case D3-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

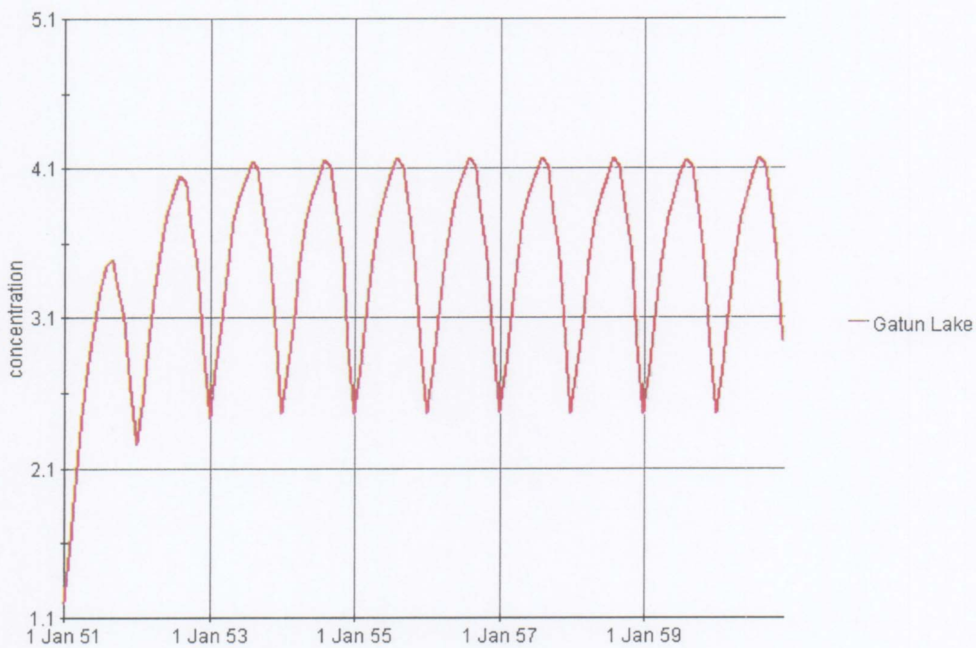


Figure D3-50, 2 Case D3-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

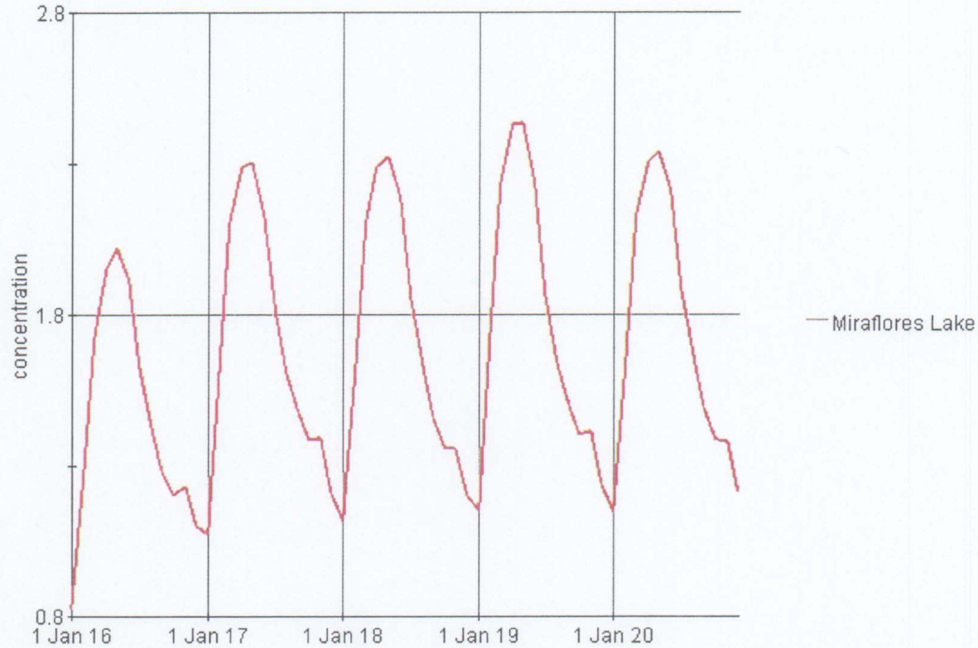


Figure D4-10, 1 Case D4-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

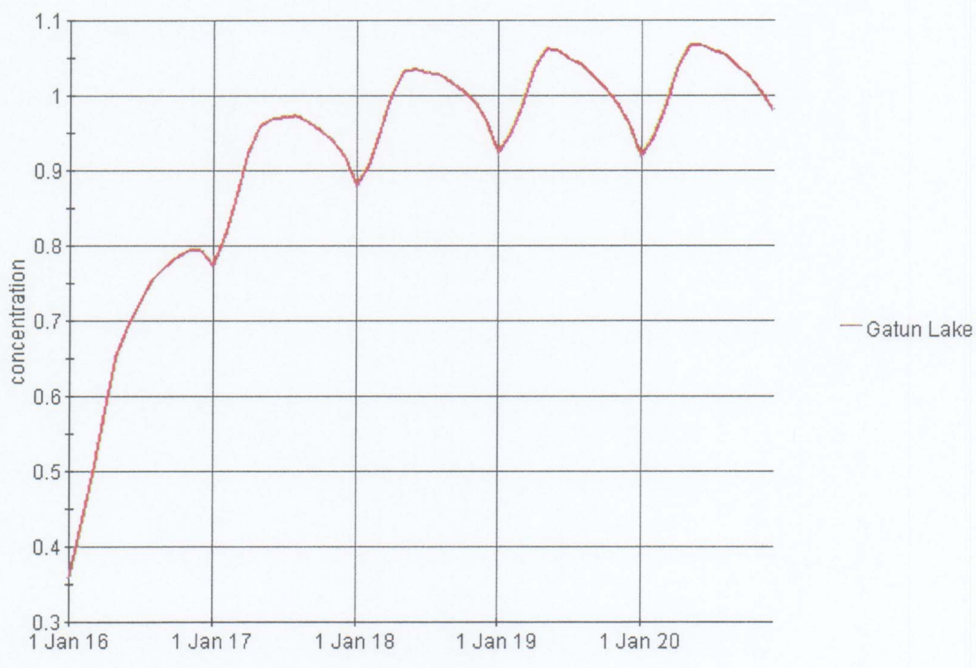


Figure D4-10, 2 Case D4-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

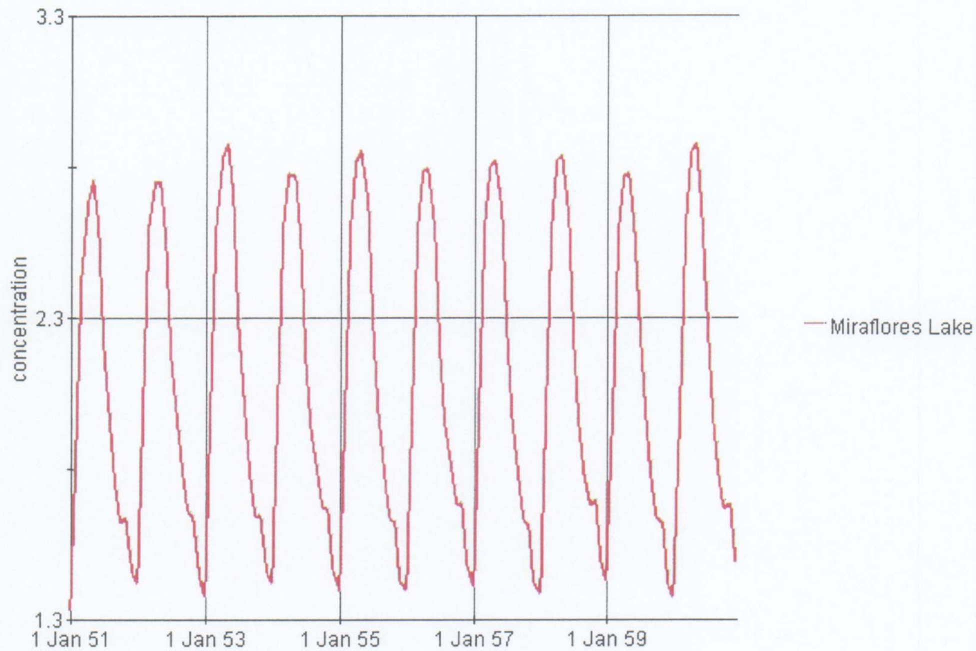
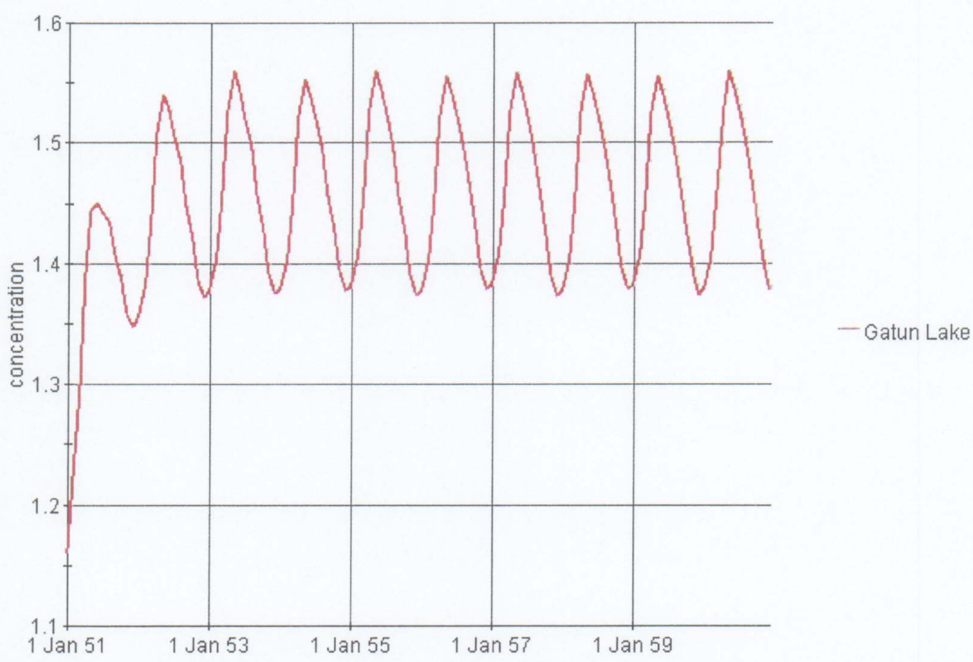


Figure D4-50, 1 Case D4-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)



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Report C
Three-lift Post-Panamax Locks

Contents Report C

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1 Introduction

The present Report C deals with the salt water intrusion of the *three-lift lock* configuration of Post-Panamax Locks on the future, third shipping lane. The salt water intrusion is additional to the salt water intrusion through the existing locks. The new three-lift locks may be provided with water saving basins.

The following items will be adressed in the present report:

- review of concept design of Consorsio Post-Panamax (CPP) for the *three-lift lock* configuration of Post-Panamax Locks;
- extension of the salt-water intrusion simulation model built for the existing situation with a new shipping lane; this new lane is is provided with *three-lift locks* and water saving basins at either side of the canal (the use of water saving basins is optional in the simulation model);
- selection of salt exchange coefficients that will be used in the simulation;
- simulation of salt water intrusion for the *three-lift lock* configuration of Post-Panamax Locks and analysis of results.

2 Concept design of CPP for three-lift lock configuration

2.1 Data provided by ACP

The next reports and drawings have been provided by ACP:

Report

Consorcio Post-Panamax (CPP)
'Diseño Conceptual de las Esclusas Post Panamax,
Task 4, C – Filling and Emptying System'
Concept report R4-C-402 rev A, 4 September 2002.

Drawings of CPP

Drawing number	Revision	Title
D3-0-003	B	Triple lift configuration. Alignment P1: nautical access.
D4-A-003	B	Triple lift configuration. General plan view.
D4-B-001	B	Triple lift configuration. Eastern lock wall: longitudinal view.
D4-B-003	D	Triple lift configuration. Lock chamber 1: plan view.
D4-B-004	B	Triple lift configuration. Lock chamber 2: plan view.
D4-B-005	D	Triple lift configuration. Lock chamber 3: plan view.
D4-B-006	B	Triple lift configuration. Cross sections lock walls.
D4-B-007	A	Triple lift configuration. Lock head 2: plan view.
D4-B-010	-	Triple lift configuration. Lock head 1: plan view.
D4-B-013	-	Triple lift configuration. Lock head 3: plan view.
D4-B-016	-	Triple lift configuration. Lock head 4: plan view.
D4-B-020	-	Triple lift configuration. Lock head 4: arrangement with pumping basin.
D4-C-001	B	Triple lift configuration. 3D-model wsb emptying system.
D4-C-002	B	Triple lift configuration. Water saving basins – filling and emptying system.

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 lock system at Pacific side

The three-lift lock configuration of Post Panamax Locks designed by CPP, connects the canal entrance at the Pacific side with Gatun Lake (Gaillard Cut). A new channel between the upper lock of the three-lock system and Gaillard Cut forms a part of the new shipping lane. This channel will be excavated at the west side of Miraflores Lake; the lake itself is by-passed. The new locks are situated west of Miraflores Locks. Each of three locks is provided with three water saving basins, arranged side by side at the east side of the locks.

The next data was taken by CPP as starting points for their design *(all levels refer to PLD)*:

Hydraulic conditions

Gatun Lake: mean water level +25.91 m, maximum water level +26.67 m, minimum water level +23.90 m.
Canal entrance at the Pacific side: mean sea level +0.30 m, extreme high tide +3.60 m, mean low tide –2.32 m, extrem low tide –3.44 m.

Lock chambers

Minimum utilizable length of lock chambers 426.8 m, width 61.0 m, minimum water depth above sills 18.3 m. Locks can be operated with or without water saving basins; in the latter case lock-to-lock water transfer is practised. The water saving rate for each individual lock chamber is minimum 60% (when water saving basins are in use). The filling or emptying time is approximately 10 minutes when water saving basins are not in use.

Post-Panamax ships

Dimensions of ships: container ships 105,000 dwt and bulk carriers 140,000 dwt.

Three-lift lock design

The CPP-design for the three-lift lock configuration at the Pacific side of the canal is schematically shown in Figure 2.1. The new locks have a width of 61 m. Each lock chamber is provided with a double set of rolling gates at both ends. The gates move in recesses, which are constructed in the floor of the lock chambers; the chamber floors themselves are fully flat without sills. The nominal length of the lock chambers between the center line of the upper gates and the center line of the lower gates is about 472 m.
When going upwards from the Pacific tailbay to Gatun Lake the steps in the floor are successively 9.95 m, 8.26 m and 8.04 m high. Floor level –20.62 m of the lower lock is designed starting from the minimum required water depth of 18.3 m and a mean low-tide water level in the tailbay of –2.32 m. Floor level +5.63 m of the forebay in Gatun Lake follows from the minimum lake level +23.90 m and the minimum required water depth of 18.3 m.

Three water saving basins are arranged side by side along each of the lock chambers (see Figures 2.1 and 3.4). The length and width of the water saving basins differ from the horizontal dimensions of the lock chambers, but the capacity of the water saving basins is such, that at least 1/5 of the water exchange volume can be saved in each basin. The three water saving basins of a lock have different bottom levels.

The filling and emptying system consists of a multiport system. The main water culverts at both sides of the locks run along the full length of the locks from the intakes in the forebay to the outlets in the tailbay. The culverts are provided with valves to facilitate a controled flow of water from forebay to upper lock, from lock to lock, and from lower lock to tailbay. Square openings (ports) connect the lock chambers with the culverts. The openings have dimensions of 2 m x 2 m and are situated in both lock walls (just above the floor) along the full chamber length, at a center to center distance of 15 m.

Each water saving basin (wsb) is connected to the longitudinal culverts by means of two gated transverse culverts (at 1/3 and 2/3 of the chamber length). Filling of a lock chamber starts with emptying of the lower wsb, than the intermediate wsb and finally the upper wsb. The remaining water portion is supplied from the adjacent higher lock or forebay. Emptying of a lock chamber occurs in a reverse sequence: first the upper wsb is filled, than the intermediate wsb and finally the lower wsb. The remaining water portion is discharged to the adjacent lower lock chamber or tailbay. Filling or emptying of a wsb stops when an equal water level is obtained in wsb and lock chamber. The same holds for the transfer of water from forebay to lock chamber etc.

2.3 Lock system at Atlantic side

Though the three-lift lock system has been designed by CPP for the Pacific side of the canal, we will assume, for the extension of the salt-intrusion simulation model, that a similar lock system will be constructed at the Atlantic side. However, we will adapt the floor levels of the locks because of the much smaller tidal variation at the Atlantic side of the canal (mean water level in the Atlantic entrance of the canal +0.06 m, extreme high tide +0.56 m, mean low tide –0.12 m, extrem low tide –0.38 m).

In the existing situation the difference between floor level of the lower locks at the Pacific side and the lower locks at the Atlantic side is about 2.0 m. When we start from extreme low tide at the Atlantic side of –0.38 m and a minimum required water depth of 18.3 m a floor level of –18.68 m is found for the lower lock of the new lock system. In the schematization we assume a floor level of –18.62 m, 2.0 m lower than the floor level of the new lower lock at the Pacific side. The floor level of the forebay can be the same as at the Pacific side, namely +5.63 m. The steps in floor level when going up from the Atlantic tailbay to the forebay in Gatun Lake are selected as 8.13 m, 8.08 m and 8.04 m successively. All other lock dimensions and the layout of water saving basins are similar as at the Pacific side, but the floor levels of water saving basins are adapted to the selected floor levels and water levels of the corresponding lock chambers. The adopted three-lift lock system at the Atlantic side is shown schematically in Figure 2.2.

2.4 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 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 2.1 Expected traffic intensities in existing and new shipping lanes

Lockage times in the three-lift locks of the new lane (with water saving basins) are estimated as 120 minutes for Panamax-Plus vessels and 150 minutes for Post-Panamax vessels in a relay mode of operation.

3 Simulation model

The salt-intrusion process through the locks on the Panama Canal is simulated with a numerical model. This model has been set up for the existing situation (see description in Report A, issued June 2003) and is extended and adapted to the situation with a new shipping lane and three-lift locks. A scheme of the extended model is shown in Figure 3.1. 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 (see Figures 3.5 and 3.6). 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, wsb's, forebays and tailbays of locks, lakes and entrances) are regarded as nodes in the numerical simulation model. The nodes and the hydraulic connections between the nodes are shown in the scheme of Figure 3.1. In the present study we name the locks as indicated in Figure 3.1: locks in the existing lanes at the Pacific side: A-west and A-east, B-west and B-east, C-west and C-east; locks in the existing lanes at the Atlantic side: D-west and D-east, E-west and E-east, F-west and F-east, locks in the new lane at the Pacific side: G, H and J; locks in the new lane at the Atlantic side: K, L and M.

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.

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 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 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. A special scenario is the scenario that describes a 'turn around' (change from northbound ship transits to southbound ship transits or reverse), and a water-release scenario that describes the water spills and water use for hydropower generation and cooling.

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, for example for each day of the week. Subsequently, day patterns are combined in a case (see scheme of Figure 3.2). A case contains information on start date and stop date of the simulation. Day patterns are handled one by one in the sequence of input. After the last day pattern has been handled the simulation model starts again with the first day pattern; this cyclical process continues until the end of the simulation. The user shall prepare a set of salt exchange coefficients (see Chapter 4) 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 3.10). 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 3.3.

3.2 Three-lift locks and wsb's in simulation model

In addition to the two existing shipping lanes a new lane with three-lift locks at both sides is defined in the simulation model. Each lock is provided with water saving basins (wsb's). Because the three wsb's of a lock are filled or emptied one after another and the sequence of filling and emptying is always the same, the set of three wsb's can for the purpose of salt-water intrusion simulation be replaced by a single wsb (see Figure 3.4). The storage capacity of this single wsb is equal to the capacity of the set of three wsb's; also the fill and emptying time is equal to the fill and emptying time of the set of three wsb's. The exchange coefficient in the salt balance is such selected that it is representative for the salt exchange between lock chamber and all three individual water saving basins (see Chapter 5). The locks in the new lane can be operated with or without wsb's in the simulation model.

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} (= $l_{lock} \cdot b_{lock}$)
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)

3.4 Ship movements and turn arounds; vessel classes

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 (see hereafter) between an uplockage and a downlockage scenario.

With the new lane included a total number of 16 different ship movements and turn arounds can be distinguished. The 3-lift locks in the new lane can be operated with or without water saving basins. Table 3.1 gives an overview of the various ship movements in the simulation model.

no	*ship movement*	*lane*	*up- or downlockage*	*remarks*
1	Pacific Ocean to Gatun Lake	west lane	Uplockage	
2	Gatun Lake to Pacific Ocean	west lane	Downlockage	
3	Pacific Ocean to Gatun Lake	east lane	Uplockage	
4	Gatun Lake to Pacific Ocean	east lane	Downlockage	
5	Pacific Ocean to Gatun Lake	new lane	Uplockage	wsb's out of use
6	Gatun Lake to Pacific Ocean	new lane	Downlockage	wsb's out of use
7	Pacific Ocean to Gatun Lake	new lane	Uplockage	wsb's in use
8	Gatun Lake to Pacific Ocean	new lane	Downlockage	wsb's in use
9	Atlantic Ocean to Gatun Lake	west lane	Uplockage	
10	Gatun Lake to Atlantic Ocean	west lane	Downlockage	
11	Atlantic Ocean to Gatun Lake	east lane	Uplockage	
12	Gatun Lake to Atlantic Ocean	east lane	Downlockage	
13	Atlantic Ocean to Gatun Lake	new lane	Uplockage	wsb's out of use
14	Gatun Lake to Atlantic Ocean	new lane	Downlockage	wsb's out of use
15	Atlantic Ocean to Gatun Lake	new lane	Uplockage	wsb's in use
16	Gatun Lake to Atlantic Ocean	new lane	Downlockage	wsb's in use

Table 3.1 Ship movements in simulation model

A turn around scenario describes the operational steps during a so-called 'turn around' (a change from northbound ship transits in a lane to southbound ship transits or reverse). In a turn around the water levels in the lock chambers are prepared for the change in ship transit direction. A total number of 16 different turn arounds, including those for the future new lane, are distinguished in the simulation model (see Table 3.2).

no	*side of canal*	*turn around*	*lane*	*remarks*
1	Pacific side	change from northbound to southbound traffic	west lane	
2	Pacific side	change from southbound to northbound traffic	west lane	
3	Pacific side	change from northbound to southbound traffic	east lane	
4	Pacific side	change from southbound to northbound traffic	east lane	
5	Pacific side	change from northbound to southbound traffic	new lane	wsb's out of use
6	Pacific side	change from southbound to northbound traffic	new lane	wsb's out of use
7	Pacific side	change from northbound to southbound traffic	new lane	wsb's in use
8	Pacific side	change from southbound to northbound traffic	new lane	wsb's in use
9	Atlantic side	change from southbound to northbound traffic	west lane	
10	Atlantic side	change from northbound to southbound traffic	west lane	
11	Atlantic side	change from southbound to northbound traffic	east lane	
12	Atlantic side	change from northbound to southbound traffic	east lane	
13	Atlantic side	change from southbound to northbound traffic	new lane	wsb's out of use
14	Atlantic side	change from northbound to southbound traffic	new lane	wsb's out of use
15	Atlantic side	change from southbound to northbound traffic	new lane	wsb's in use
16	Atlantic side	change from northbound to southbound traffic	new lane	wsb's in use

Table 3.2 Turn arounds 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 3.3 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 lockage operations without a ship.

The vessels which use the new shipping lane, are represented by three additional vessel classes (see Table 3.4). 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 2.1.

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

3.5 Steps in scenarios for ship movements

In this section the various steps in scenarios for ship movements in the new lane with a three-lift lock system are described. A distinction is made between locks without wsb's and locks with wsb's.

3.5.1 Locks without wsb's

The subsequent steps in the scenarios that describe ship movements in a three-lift lock system without wsb's, are similar as described in Report A for ship movements in the existing three-lift lock system at the Atlantic side. As an example next table shows the steps which are distinguished 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
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.5 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb's

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

Table 3.6 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks without wsb's.

The steps in the scenarios for ship movements Atlantic Ocean → Gatun Lake en Gatun Lake → Atlantic Ocean are similar, apart from the names of the locks (tailbay lock G = tailbay lock K, lock G = lock K, lock H = lock L, lock J = lock M, forebay lock J = forebay lock M).

3.5.2 Locks with wsb's

More steps are required in scenarios for ship movements in a three-lift lock system with wsb's. As an example next Table 3.7 shows the subsequent steps in the uplockage scenario 'ship movement Pacific Ocean → Gatun Lake' (see also Figure 3.5):

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
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.7 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb.

The subsequent steps in the downlockage scenario 'ship movement Gatun Lake → Pacific Ocean' are shown in Table 3.8 (see also Figure 3.6):

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

Table 3.8 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb's.

The steps in the scenarios for ship movements Atlantic Ocean → Gatun Lake and Gatun Lake → Atlantic Ocean are similar, apart from the names of the locks (tailbay lock G = tailbay lock K, lock G = lock K, lock H = lock L, lock J = lock M, forebay lock J = forebay lock M).

3.6 Steps in scenarios for turn arounds

A turn around scenario contains the various steps which are required to prepare the locks for a change in ship transit direction. The subsequent steps in turn arounds in the new lane with a three-lift lock system are described in this section. A distinction is made between locks without wsb's and locks with wsb's.

3.6.1 Locks without wsb's

As an example we present the steps in the 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 (see also Figure 2.1). The water levels in locks G and H have to be lowered. The procedure is similar as described in Report A for the existing three-lift lock system at the Atlantic side. Three steps are necessary:

Low basin	*High basin*	*Operation*
Tailbay Lock G	Lock G	Equalize water levels
Lock G	Lock H	Equalize water levels
Tailbay Lock G	Lock G	Equalize water levels

Table 3.9 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage) transits. New lane, three-lift locks without wsb's.

The steps in the turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)' are shown in next table. After passage of the last southbound ship (downlockage), the water levels in lock chambers G, H and J are low. The water levels in locks H and J have to be raised. Water in the forebay of lock J is exchanged with water in Gatun Lake (density flows).

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

Table 3.10 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage) transits. New lane, three-lift locks without wsb's.

Steps in turn arounds at the Atlantic side are similar, apart from the names of the locks (tailbay lock G = tailbay lock K, lock G = lock K, lock H = lock L, lock J = lock M, forebay lock J = forebay lock M).

3.6.2 Locks with wsb's

Locks with wsb's require more steps. As an example the steps in the turn around scenario 'Pacific side, change from northbound (uplockage) to southbound (downlockage)' are shown in Table 3.11. After passage of the last northbound ship (uplockage) the water levels in lock chambers G, H and J are high and the wsb's are empty. The water levels of locks G and H have to be lowered and the corresponding wsb's filled.
The procedure shown in Table 3.11 is the formal procedure. As can be seen the wsb's of lock G are filled and subsequently emptied. In a next step the wsb's of lock G are filled again. These repeated operations with the wsb's seem unnecessary.
Indeed, in practice a faster method is possible by omitting the steps in which the wsb's of lock G are filled and emptied for the first time. Instead, about 40% of the lockage water is discharged directly from lock G into the tailbay. However, this method requires the measurement of the water level in both lock G and the tailbay during discharging of water and calls for special operation procedures.
The formal procedure that is applied in the simulation model, is safe and independent of measurements and operation procedures: water between basins is exchanged until the equilibrium level is reached.

Low basin	*High basin*	*Operation*
Tailbay Lock G	Lock G	Fill wsb's of lock G
Tailbay Lock G	Lock G	Equalize water levels
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

Table 3.11 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage) transits. New lane, three-lift locks with wsb.

The steps in the turn around scenario 'Pacific side, change from southbound (downlockage) to northbound (uplockage)' are shown in Table 3.12. The water levels in lock chambers G, H and J are low after passage of the last southbound ship (downlockage) and the wsb's are filled. The water levels in locks H and J have to be raised and the corresponding wsb's emptied.

The formal procedure shown in Table 3.12 contains steps in which the wsb's of lock J are emptied, filled and emptied again. Again, a faster method is possible by omitting the first two wsb actions, and instead discharging about 40% of the lockage water directly from lock J into lock H. But because this will require the measurement of the water level in both lock J and lock H during discharging and special operation procedures the safe formal procedure is preferred in the simulation model.

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

Table 3.12 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage) transits. New lane, three-lift locks with wsb.

Steps in turn arounds at the Atlantic side are similar, apart from the names of the locks (tailbay lock G = tailbay lock K, lock G = lock K, lock H = lock L, lock J = lock M, forebay lock J = forebay lock M).

3.7 Dimensions of locks, wsb's and forebays / tailbays

The characteristic dimensions of locks, wsb's and forebays in the new shipping lane are indicated in Table 3.13 (see also Figures 2.1 and 2.2).

basin	*nominal length*	*width*	*nominal, mean water level (m to PLD)*		*flooor level = sill level*	*step in floor*	*coping level*
	(m)	*(m)*	*high*	*low*	*(m to PLD)*	*(m)*	*(m to PLD)*
Pacific side							
Lock G	472	61	+8.83	+0.30	-20.62	9.95	+12.46
wsb's Lock G					-1.76*		
Lock H	472	61	+17.37	+8.83	-10.67	8.26	+20.95
wsb's Lock H					+8.01*		
Lock J	472	61	+25.91	+17.37	-2.41	8.04	+29.67
wsb's Lock J					+16.39*		
Forebay Lock J			+25.91		+5.63		+29.67
Atlantic side							
Lock K	472	61	+8.68	+0.06	-18.62	8.13	+12.17
wsb's Lock K					+0.24*		
Lock L	472	61	+17.30	+8.68	-10.49	8.08	+20.94
wsb's Lock L					+8.19*		
Lock M	472	61	+25.91	+17.30	-2.41	8.04	+29.67
wsb's Lock M					+16.39*		
Forebay Lock M			+25.91		+5.63		+29.67

*) floor level of lower wsb

Table 3.13 Dimensions of locks, wsb's and forebays, new shipping lane

The characteristic dimensions of locks and forebays / tailbays in the existing lanes are shown in Table 3.14.

basin	*nominal length* *(m)*	*width* *(m)*	*nominal, mean water level (m to PLD)*		*floor level / sill level* *(m to PLD)*	*step sill - sill* *(m)*	*coping level* *(m to PLD)*
			high	*low*			
Pacific side							
Lock A (A-west & A-east)	329.2	33.5	+7.92	+0.30	-15.54 / -15.24	9.65	+9.75
Lock B (B-west & B-east	332.1	33.5	+16.46	+7.92	-6.20 / -5.59	9.04	+17.88
Forebay lock B (B-west & B-east)			+16.46		+3.35 (near intake) / +3.45		
Tailbay Lock C (C-west & C-east)			+16.46		+2.59 (near outlet) / +3.69		
Lock C (C-west & C-east)	332.1	33.5	+25.91	+16.46	+3.35 / +3.96	7.42	+28.04
Forebay lock C (C-west & C-east)			+25.91		+11.38 (near intake) / +11.38		
Atlantic side							
Lock D (D-west & D-east)	329.2	33.5	+8.54	+0.06	-13.51 / -12.90	8.76	+10.57
Lock E (E-west & E-east)	329.2	33.5	+17.38	+8.54	-4.67 / -4.14	8.71	+19.58
Lock F (F-west & F-east)	332.1	33.5	+25.91	+17.38	+4.17 / +4.57	6.81	+28.04
Forebay lock F (F-west & F-east)			+25.91		+4.27 (near intake) / +11.38		

Table 3.14 Dimensions of existing locks and forebays / tailbays

The dimensions and properties of basins in the simulation model are as follows:

New locks

The nominal lock chamber length is the size between the centre line of the upper rolling gates and the centre line of the lower rolling gates and equals about 472 m for all lock chambers. The nominal length multiplied by the chamber width and the water-level difference between adjacent chambers determines the quantity of lockage water that is transferred in downstream direction during uplockage or downlockage of a ship. Also the gate recesses contribute to the lockage water. This is accounted for in the simulation model by increasing the area of the lock chambers with the area of two gate recesses; doing so the nominal length of the lock chamber is increased with about 2 x 16.5 m, giving a total length of 505 m. This size is used in the numerical simulations. The new locks have flat floors without sills. Coping level corresponds to the top level of the lock walls.

Forebays new locks

The water volume of the forebays in Gatun Lake is arbitrarely computed as the product of length 505 m (= nominal lock chamber length + contribution gate recesses), width 61 m (= lock chamber width) and water depth above the adjacent lock floor. In formula form:

$V_{forebay} = A_{forebay} \cdot (h_{lake} - f_{lock}) = 505\ m \cdot 61\ m \cdot (h_{lake} - f_{lock})$

Water saving basins new locks

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

Existing locks

The nominal lock chamber length is the size between upper gate and lower gate of a lock This size determines the quantity of lockage water and is used in the simulations. Floor level corresponds to the flat, deeper part of the lock chambers; the sills protrude 0.3 m – 0.6 m (1 ft – 2 ft) above floor level. Lock chamber floors are thus at a lower elevation than the sills. Coping level corresponds to the top of the chamber walls.

Forebays and tailbays existing locks

The water volume of the forebays in Miraflores Lake and Gatun Lake and the tailbays in Miraflores Lake is arbitrarely computed as the product of length 330 m (= average nominal lock chamber length), width 33.5 m (= lock chamber width) and water depth above the adjacent lock sill. In formula form:

$V_{forebay} = A_{forebay} \cdot (h_{lake} - f_{sill}) = 330\ m \cdot 33.5\ m \cdot (h_{lake} - f_{sill})$
$V_{tailbay} = A_{tailbay} \cdot (h_{lake} - f_{sill}) = 330\ m \cdot 33.5\ m \cdot (h_{lake} - f_{sill})$

Function of forebays and taillbays 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.
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.

In the simulations we put:

lock chambers

V_{lock}	$= l_{lock} . b_{lock} . d_{lock}$ = water volume of lock chamber
l_{lock}	= nominal length of lock chamber; existing locks see Table 3.14, new locks 505 m
b_{lock}	= width of lock chamber (see Tables 3.13 and 3.14)
h_{lock}	= water level (in m to PLD)
f_{lock}	= floor level (in m to PLD; see Tables 3.13 and 3.14)
d_{lock}	= water depth in lock chamber = $h_{lock} - f_{lock}$
$maxh_{lock}$	= highest water level in lock chamber = coping level (in m to PLD)
$minh_{lock}$	= lowest water level in lock chamber; existing locks: sill level + 10 m (in m to PLD); new locks: floor level + 10 m (in m to PLD)

forebays (Gatun Lake, Miraflores Lake) and tailbays (Miraflores Lake) existing locks

$V_{forebay}$	$= 330 \text{ m} . 33.5 \text{ m} . (h_{lake} - f_{sill})$
$V_{tailbay}$	$= 330 \text{ m} . 33.5 \text{ m} . (h_{lake} - f_{sill})$

forebays new locks (Gatun Lake)

$V_{forebay}$	$= 505 \text{ m} . 61 \text{ m} . (h_{lake} - f_{lock})$

water saving basins new locks

V_{wsb}	$= l_{wsb} . b_{wsb} . d_{wsb}$
l_{wsb}	= length of wsb in simulation = 505 m
b_{wsb}	= width of wsb in simulation = 61 m
d_{wsb}	= water depth of wsb (total depth of the three individual wsb's)
$maxV_{wsb}$	= maximum water volume of wsb; about 15 m x 505 m x 61 m (450000 m^3)
$minV_{wsb}$	= minimum water volume in wsb = 0.01 * $maxV_{wsb}$ (4500 m^3 corresponding to about 0.15 m water depth)

3.8 Miraflores Lake and Gatun Lake

3.8.1 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, evapotranspiration, 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 were 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.
The same water levels are used as input in the simulation model for the new situation, after realization of the new shipping lane. The average water level values are shown in next table together with the corresponding water volume.

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 3.15 Gatun Lake: representative water level and corresponding water volume

The water levels of Gatun Lake and Miraflores Lake which are used in the simulation model are shown in Figure 3.7.

3.8.2 Water releases

The water levels of Miraflores Lake and Gatun Lake are controled by spillways. When the water level exceeds a maximum value, the surplus water is spilled. Water of Gatun Lake is also used for hydropower generation, water of Miraflores Lake for cooling.
The daily spilled water quantities of Gatun Lake and water quantities used for hydropower generation have been averaged for all months in the period 1992 – 2001. The average values of month-averages (January, February, ... December) in this period were used in the validation of the simulation model (existing situation, see Report A); they were regarded as typical, representative values. Since the locks on the new shipping lane cause extra water losses, 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.

In a *baseline scenario* we start from the assumption that all extra water losses from Gatun Lake caused by the new locks are compensated by an equal quantity of fresh water, that is supplied from new water sources. Consequently, the present water levels and water releases will not change and we will use the representative water-release quantities presented in Table 3.16 as input in the simulation model.

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 3.16 Gatun Lake: representative values of daily spilled water quantities and water quantities used for hydropower (baseline scenario)

In a *second scenario* we assume that the extra water losses caused by 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. The extra water losses of the new locks are growing when the Post-Panamax shipping increases. Table 3.17 presents the extra water losses of the new locks in this scenario; the values are based on the ship-traffic projections of ACP for the next 50 years (semi-convoy mode of operation) and on the assumption of 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 / 3) m * 505 m * 61 m * 2 =

about 5.10^5 m^3 (when wsb's are in use with 60% water saving rate the water loss amounts to 2.10^5 m^3).

Period after opening of new lane	*Post-Panamax ship transits (number per day)*	*Extra water losses (10^6 m^3/day)*	*Extra water losses in case of wsb's (10^6 m^3/day)*
month 1	2	1.00	0.40
year 1	5	2.50	1.00
year 5	6	3.00	1.20
year 10	7	3.50	1.40
year 20	9	4.50	1.80
year 50	15	7.50	3.00

Table 3.17 Extra water losses after opening of third, new lane

In the *second scenario* the water releases at Gatun Dam are as follows (reduction for extra water losses of new lane included):

Month	*Total water release year 0 (10^6 m^3 per day)*	*Total water release month 1 (10^6 m^3 per day)*	*Total water release year 1 (10^6 m^3 per day)*	*Total water release year 5 (10^6 m^3 per day)*	*Total water release year 10 (10^6 m^3 per day)*	*Total water release year 20 (10^6 m^3 per day)*	*Total water release year 50 (10^6 m^3 per day)*
January	4.61	3.61	2.11	1.61	1.11	0.11	0.00
February	0.60	0.00	0.00	0.00	0.00	0.00	0.00
March	0.20	0.00	0.00	0.00	0.00	0.00	0.00
April	0.16	0.00	0.00	0.00	0.00	0.00	0.00
May	0.94	0.00	0.00	0.00	0.00	0.00	0.00
June	3.63	2.63	1.13	0.63	0.13	0.00	0.00
July	5.55	4.55	3.05	2.55	2.05	1.05	0.00
August	6.58	5.58	4.08	3.58	3.08	2.08	0.00
September	8.32	7.32	5.82	5.32	4.82	3.82	0.82
October	8.23	7.23	5.73	5.23	4.73	3.73	0.73
November	11.60	10.60	9.10	8.60	8.10	7.10	4.10
December	12.63	11.63	10.13	9.63	9.13	8.13	5.13

Table 3.18 Gatun Lake: representative values of daily released water quantities (second scenario; locks in new lane without wsb's)

When the wsb's of the locks in the new lane are active the water losses are smaller and the water releases at Gatun Dam become:

Month	*Total water release year 0 (10^6 m^3 per day)*	*Total water release month 1 (10^6 m^3 per day)*	*Total water release year 1 (10^6 m^3 per day)*	*Total water release year 5 (10^6 m^3 per day)*	*Total water release year 10 (10^6 m^3 per day)*	*Total water release year 20 (10^6 m^3 per day)*	*Total water release year 50 (10^6 m^3 per day)*
January	4.61	4.21	3.61	3.41	3.21	2.81	1.61
February	0.60	0.20	0.00	0.00	0.00	0.00	0.00
March	0.20	0.00	0.00	0.00	0.00	0.00	0.00
April	0.16	0.00	0.00	0.00	0.00	0.00	0.00
May	0.94	0.54	0.00	0.00	0.00	0.00	0.00
June	3.63	3.23	2.63	2.43	2.23	1.83	0.63
July	5.55	5.15	4.55	4.35	4.15	3.75	2.55
August	6.58	6.18	5.58	5.38	5.18	4.78	3.58
September	8.32	7.92	7.32	7.12	6.92	6.52	5.32
October	8.23	7.83	7.23	7.03	6.83	6.43	5.23
November	11.60	11.20	10.60	10.40	10.20	9.80	8.60
December	12.63	12.23	11.63	11.43	11.23	10.83	9.63

Table 3.19 Gatun Lake: representative values of daily released water quantities (second scenario; locks in new lane with wsb's)

The daily water-release quantities of Tables 3.18 and 3.19 are used in the simulations.

The daily spilled water quantities of Miraflores Lake and the water quantities used for cooling at Miraflores are shown in Table 3.20. 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 3.20 Miraflores Lake: daily spilled / used water quantities in 2001

The values in Table 3.20 are not suited for use in the simulation model, because they are not representative for a longer period of time. To get better 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 3.21; these values are regarded as representative values and are used in the simulation model. Since the new lane does not effect the water level of Miraflores Lake the water release quantities are valid both for the *baseline scenario* and the *second scenario.*

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 3.21 Miraflores Lake: representative quantities of daily spilled water and water used for cooling (baseline scenario and second scenario)

The daily water releases of Gatun Lake and Miraflores Lake are shown in Figure 3.8 (baseline scenario).

3.8.3 Effect of water level changes and water releases

Water levels and corresponding water volumes of Gatun Lake and Miraflores Lake are prescribed for each day of a case in the simulation model. Also the water-release quantities are prescribed through special water-release scenarios in the day pattern. The effects of water level changes on the salt concentration of the lakes are evaluated at the start of each day; the effects of water releases are evaluated when the water-release scenarios are executed (see also Section 4.6).

3.9 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 it are the period and the amplitude that count, rather than a full reproduction of the 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 3.9).

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 3.10).

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 3.22 Salt concentration in tailbays at Pacific and Atlantic side

The salt concentrations presented in the above table are also shown in Figure 3.11.

3.10 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. In addition, an initial value must be given to the salt concentrations in the lock chambers and wsb's, 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. Initial water levels in the lock chambers are by default selected from Tables 3.13 and 3.14 (nominal, mean high water level); initial water volumes of wsb's are by default set to '$minV_{wsb}$' (see Section 3.7).

4 Evaluation of nodal status parameters

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.
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, see Section 3.10. 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 Section 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, 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. 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 equations for ship movements and turn arounds in the *existing* shipping lanes are explained in Report A; they will not be repeated here.

4.1 Ship movements new lane, three-lift locks without wsb's

The evaluation of nodal status parameters for ship movements in the new shipping lane provided with a three-lift lock system without wsb's, is similar as described in Report A for the existing lanes with three-lift locks (Atlantic side of the Panama Canal). Reference is made to Report A for a description.

4.2 Ship movements new lane, three-lift locks with wsb's, uplockage

Two 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

The time-dependent exchange of salt water between forebays / tailbays and lakes is handled in a 'special step'.

For the various combinations of basins (tailbays, locks with wsb's, forebays, lakes) the equations which describe the water balance and the salt balance within a basic step of the locking process are presented.

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

- the water volume V_{save} that is spilled to and supplied from the wsb's of adjacent locks is equal to maximum 60% of the water volume V_{ref} that would be exchanged between these locks when no wsb's were present
- 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
- the same starting points hold when low basin is tailbay and high basin is lock, or when low basin is lock and high basin is forebay.

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:

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

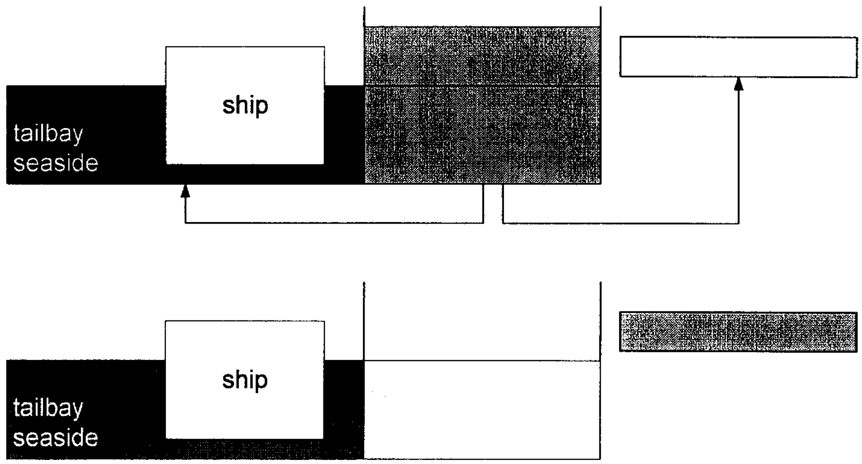
with: e_{x0} = value of e_x for S = 0

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 that is filled, and salt withdrawal from the wsb 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

step I: the water level in the low basin (with ship) is equalized with the water level in the high basin (without ship); water is transferred from high basin to low basin; if relevant: the wsb's of the lower lock are emptied, the wsb's of the higher lock are filled

low basin = tailbay seaside, high basin = lock



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

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

$V_{high2} = d_{high2} \cdot A_{high}$

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

$V_{save} = 0.6 \cdot V_{ref}$

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

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

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

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

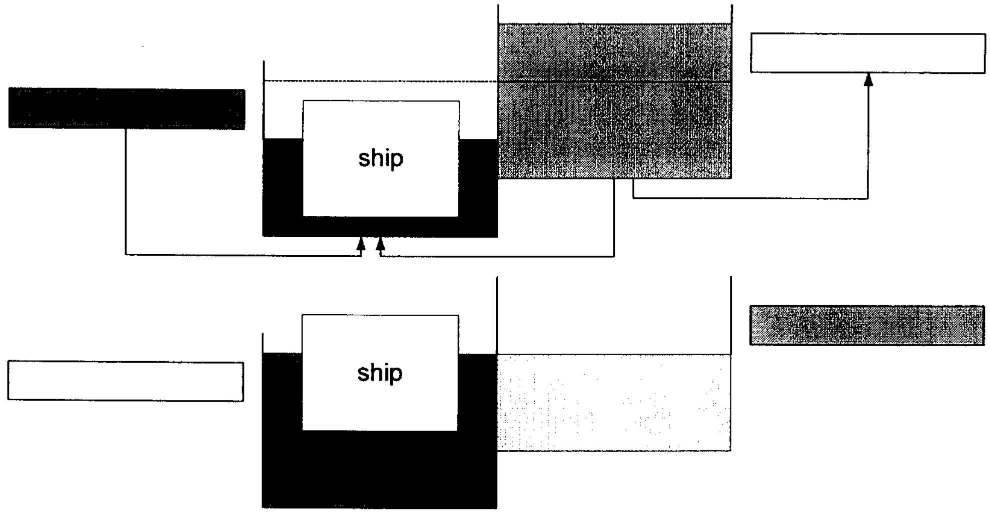
salt balance

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 = lock



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsbhigh1}$, $V_{wsblow1}$

$$h_{low2} = h_{low1} + \frac{A_{high} \cdot (h_{high1} - h_{low1})}{(A_{low} + A_{high})}$$

check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$

$h_{high2} = h_{low2}$

check: $h_{high2} < minh_{high}$?
if yes: $h_{high2} = minh_{high}$
$h_{low2} = h_{high2}$

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

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

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

$V_{high2} = d_{high2} \cdot A_{high}$

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

$V_{save} = 0.6 \cdot V_{ref}$

$V_{wsblow2} = V_{wsblow1} - V_{save}$

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

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

check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$
$V_{wsblow2} = V_{wsblow1} - V_{save}$

salt balance

Known values at the beginning of step: c_{high1}, c_{low1}, $c_{wsbhigh1}$, $c_{wsblow1}$

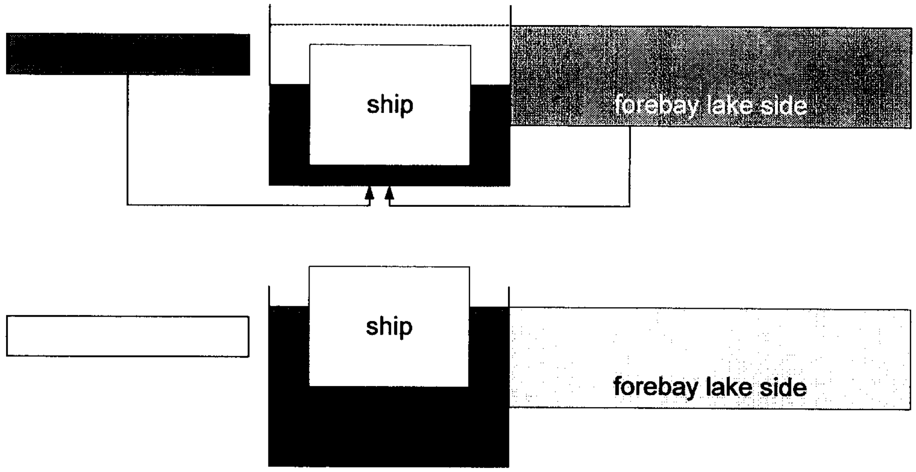
$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1}) + (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1})}{V_{low2}}$$

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

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

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

low basin = lock, high basin = forebay lake side



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
$h_{high2} = h_{high1} = h_{lake}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = (d_{low2} \,.\, A_{low}) - S$
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \,.\, A_{forebay}$
$V_{ref} = (h_{low2} - h_{low1}) \,.\, A_{low}$

$V_{save} = 0.6 \,.\, V_{ref}$
$V_{wsblow2} = V_{wsblow1} - V_{save}$
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}, $c_{wsblow1}$

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

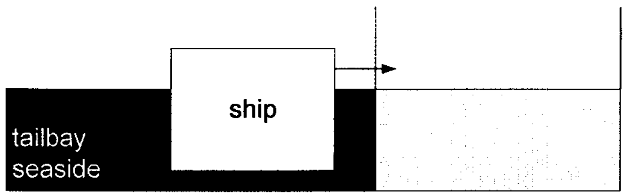
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

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

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

step II: the 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

low basin = tailbay sea side, high basin = lock



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}

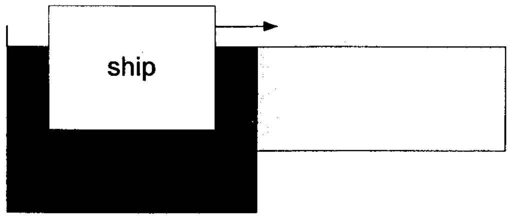
$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1}$$
$$V_{high2} = V_{high1} - S$$
$$V_{ref} = V_{high1}$$

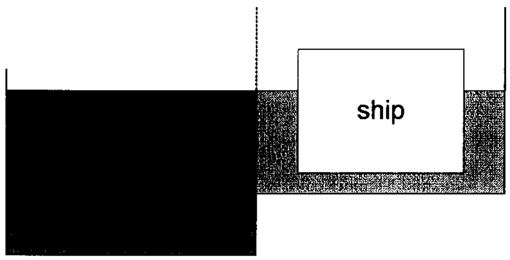
salt balance

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

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

low basin = lock, high basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{low2} = h_{low1}$
$d_{low2} = d_{low1}$
$V_{low2} = V_{low1} + S$
$h_{high2} = h_{high1}$
$d_{high2} = d_{high1}$
$V_{high2} = V_{high1} - S$
$V_{ref} = V_{high1}$

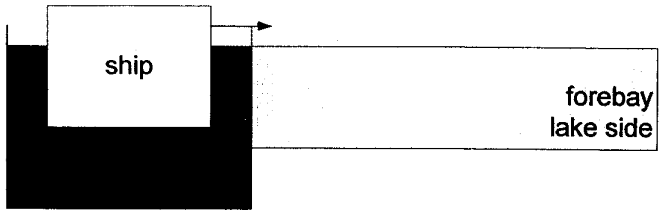
salt balance

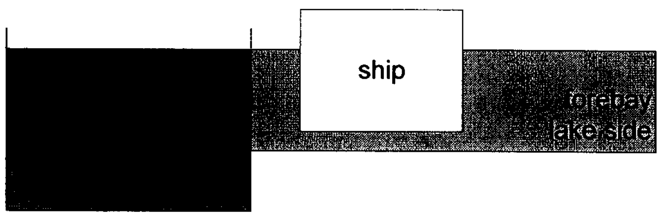
Known values at the beginning of step: c_{high1}, c_{low1}

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

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

low basin = lock, high basin = forebay lake side





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$$h_{low2} = h_{low1}$$
$$d_{low2} = d_{low1}$$
$$V_{low2} = V_{low1} + S$$
$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1} = d_{forebay}$$
$$V_{high2} = V_{high1} = V_{forebay}$$
$$V_{ref} = V_{high1}$$

salt balance

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

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

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

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

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 an uplocking ship has passed the forebay or after a turn around the salt concentration in the forebay has changed. Density differences exist between the water in the forebay and the water in the lake, and as a result density-driven exchange flows occur. 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. 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}	= 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

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull} = 1$.
A period T = 3600 s is selected for the forebays in Gatun Lake starting from the assumption that the propagation velocity of a salt tongue is in the order of 0.1 – 0.2 m/s.

4.3 Ship movements new lane, three-lift locks with wsb's, downlockage

Two 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

The time-dependent exchange of salt water between forebays / tailbays and lakes is handled in a 'special step'.
For the various combinations of basins (tailbays, locks with wsb's, forebays) the equations which describe the water balance and the salt balance within a basic step of the locking process are presented.

The next starting points hold in the set up of the water balance and salt balance in **step I**:
- the water volume V_{save} that is spilled to and supplied from the wsb's of adjacent locks is equal to maximum 60% of the water volume V_{ref} that would be exchanged between these locks when no wsb's were present
- 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
- the same starting points hold when low basin is tailbay and high basin is lock, or when low basin is lock and high basin is forebay.

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:

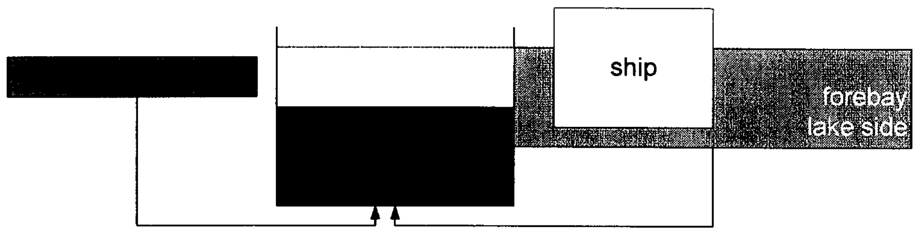
$$e_x = \left(1 - \frac{S}{V_{ref}}\right) . e_{x0}$$

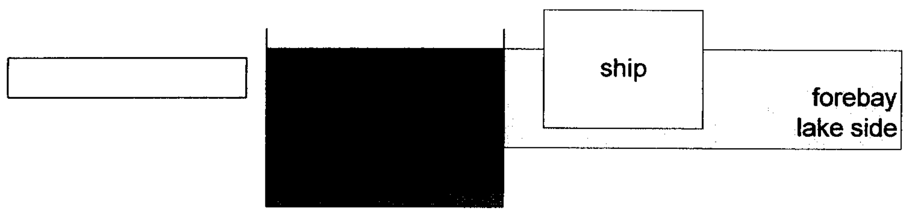
with: e_{x0} = value of e_x for S = 0

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 that is filled, and salt withdrawal from the wsb 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

step I: the water level in the low basin (without ship) is equalized with the water level in the high basin (with ship) ; water is transferred from high basin to low basin; if relevant: the wsb's of the lower lock are emptied, the wsb's of the higher lock are filled

high basin = forebay lake side, low basin = lock





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
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{save} = 0.6 \cdot V_{ref}$
$V_{wsblow2} = V_{wsblow1} - V_{save}$
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}, $c_{wsblow1}$

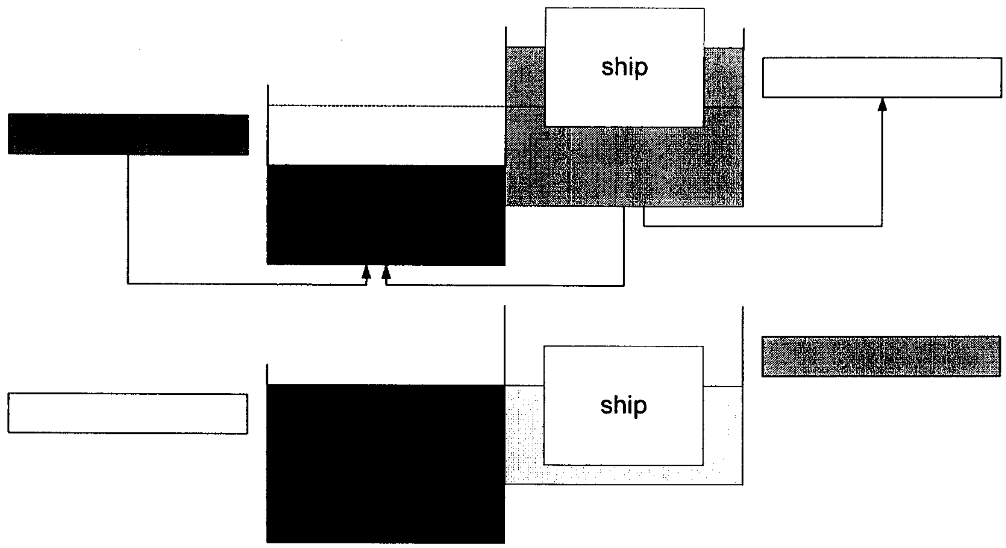
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

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

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

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

high basin = lock, low basin = lock



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsbhigh1}$, $V_{wsblow1}$

$$h_{high2} = h_{high1} - \frac{A_{low} \cdot (h_{high1} - h_{low1})}{(A_{low} + A_{high})}$$

check: $h_{high2} < minh_{high}$?
if yes: $h_{high2} = minh_{high}$
$h_{low2} = h_{high2}$
check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
$h_{high2} = h_{low2}$
$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = (d_{high2} \cdot A_{high}) - S$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{save} = 0.6 \cdot V_{ref}$
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$
check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$
$V_{wsblow2} = V_{wsblow1} - V_{save}$
check: $V_{wsblow2} < minV_{wsblow}$?
if yes: $V_{wsblow2} = minV_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$

salt balance

Known values at the beginning of step: c_{high1}, c_{low1}, $c_{wsbhigh1}$, $c_{wsblow1}$

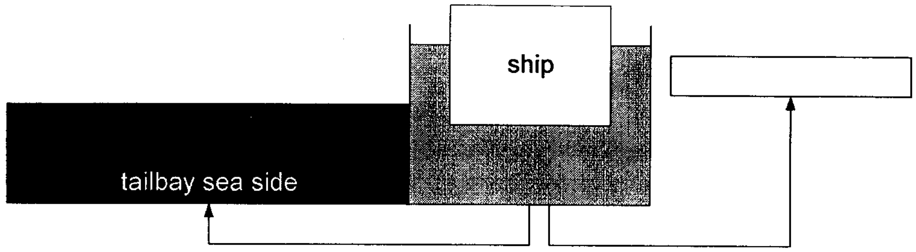
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_{wsbfill} \cdot V_{save} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1})}{V_{high2}}$$

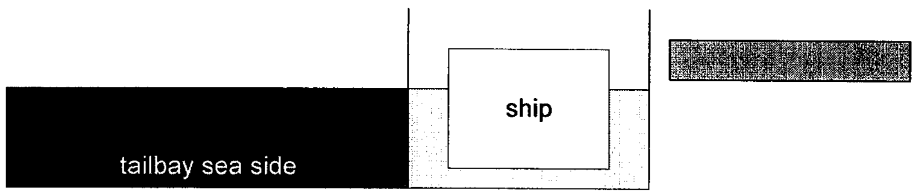
$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1}) + (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1})}{V_{low2}}$$

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

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

high basin = lock, low basin = tailbay sea





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

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

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

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

$V_{save} = 0.6 \, . \, V_{ref}$

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

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

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

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

salt balance

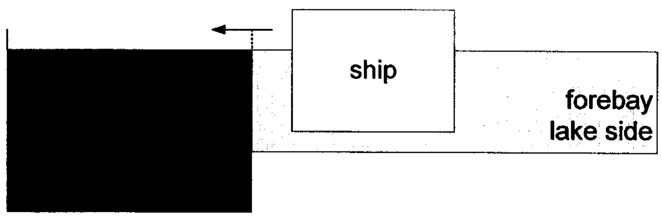
Known value at the beginning of step: c_{high1}, $c_{wsbhigh1}$

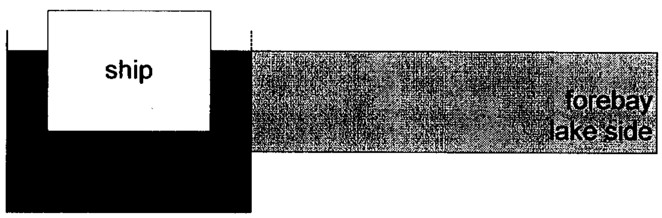
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_{wsbfill} \cdot V_{save} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1})}{V_{high2}}$$

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

step II: the 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

high basin = forebay lake side, low basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1} = d_{forebay}$$
$$V_{high2} = V_{high1} = V_{forebay}$$
$$h_{low2} = h_{low1}$$
$$d_{low2} = d_{low1}$$
$$V_{low2} = V_{low1} - S$$
$$V_{ref} = V_{high2} = V_{forebay}$$

salt balance

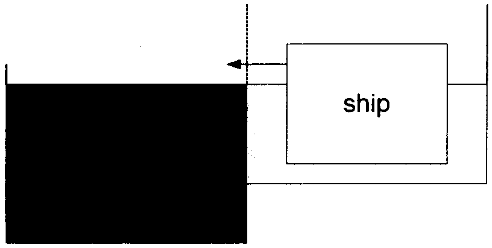
Known values at the beginning of step: c_{high1} ($= c_{forebay1}$), c_{low1}, c_{lake1}

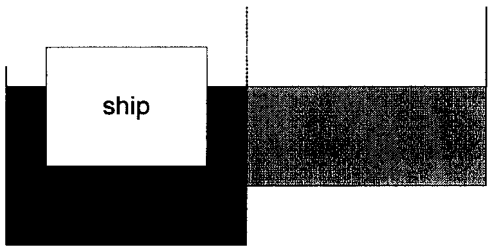
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) + e_x \cdot V_{ref} \cdot (c_{low1} - c_{high1}) + (S \cdot c_{low1}) - (S \cdot c_{high1})}{V_{high2}} = c_{forebay2}$$

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

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

high basin = lock, low basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{high2} = h_{high1}$
$d_{high2} = d_{high1}$
$V_{high2} = V_{high1} + S$
$h_{low2} = h_{low1}$
$d_{low2} = d_{low1}$
$V_{low2} = V_{low1} - S$
$V_{ref} = V_{high2}$

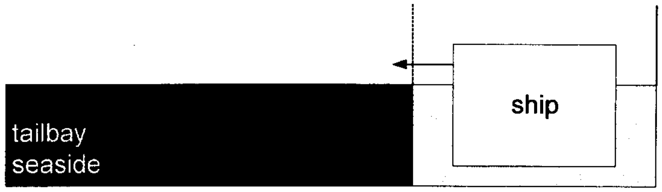
salt balance

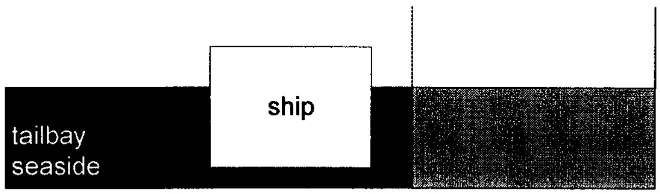
Known values at the beginning of step: c_{high1}, c_{low1}

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

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

high basin = lock, low basin = tailbay seaside





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}

$h_{high2} = h_{high1}$
$d_{high2} = d_{high1}$
$V_{high2} = V_{high1} + S$
$V_{ref} = V_{high2}$

salt balance

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

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

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. Density differences exist between the water in the forebay and the water in the lake, and as a result density-driven exchange flows occur. 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 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. 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}	= 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

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull} = 1$.
A period T = 3600 s is selected for the forebays in Gatun Lake starting from the assumption that the propagation velocity of a salt tongue is in the order of 0.1 – 0.2 m/s.

4.4 Turn arounds new lane, three-lift locks without wsb's

The evaluation of nodal status parameters in scenarios for turn arounds in the new shipping lane provided with a three-lift lock system without wsb's, is similar as described in Report A for the existing lanes with three-lift locks (Atlantic side of the Panama Canal). Reference is made to Report A for a description.

4.5 Turn arounds new lane, three-lift locks with wsb's

4.5.1 Turn around Pacific side; change from northbound (uplockage) to southbound (downlockage) transits

After the last northbound vessel has passed the locks (uplockage), the water levels in lock chambers G, H and J are high (see also Figure 2.1) and the wsb's are empty. The water levels of locks G and H have to be lowered and the corresponding wsb's filled. The equations which describe the water balance and the salt balance for these actions are similar as described in Section 4.2, uplockage, step I (submerged volume S of ship = 0). In next table reference is made to the relevant cases of this section.

Low basin	*High basin*	*Operation*	*Section 4.2, uplockage, step I Case*
Tailbay Lock G	Lock G	Fill wsb's of lock G	low basin = tailbay seaside,
Tailbay Lock G	Lock G	Equalize water levels	high basin = lock
Lock G	Lock H	Empty wsb's of lock G	low basin = lock ,
Lock G	Lock H	Fill wsb's of lock H	high basin = lock
Lock G	Lock H	Equalize water levels	
Tailbay Lock G	Lock G	Fill wsb's of lock G	low basin = tailbay seaside,
Tailbay Lock G	Lock G	Equalize water levels	high basin = lock

Table 4.1 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage) transits. New lane, three-lift locks with wsb.

4.5.2 Turn around Pacific side; change from southbound (downlockage) to northbound (uplockage) transits

The water levels in lock chambers G, H and J are low after passage of the last southbound ship (downlockage) and the wsb's are filled. The water levels in locks H and J have to be raised and the corresponding wsb's emptied. The equations which describe the water balance and the salt balance for these actions are similar as described in Section 4.3, downlockage, step I (submerged volume S of ship = 0). In next table reference is made to the relevant cases of this section. The actions are concluded with the special step described at the end of Section 4.3.

High basin	*Low basin*	*Operation*	*Section 4.3, downlockage, step I Case*
Forebay Lock J	Lock J	Empty wsb's of lock J	high basin = lock, low basin = tailbay seaside
Forebay Lock J	Lock J	Equalize water levels	
Lock J	Lock H	Fill wsb's of lock J	high basin = lock, low basin = lock
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	high basin = lock, low basin = tailbay seaside
Forebay Lock J	Lock J	Equalize water levels	
Gatun Lake	Forebay Lock J	(Density flows)	special step of Section 4.3

Table 4.2 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage) transits. New lane, three-lift locks with wsb.

4.5.3 Turn arounds Atlantic side

Steps in turn-arounds scenarios for the Atlantic side are similar as steps in turn-around scenarios for the Pacific side, apart from the names of the locks (tailbay lock G = tailbay lock K, lock G = lock K, lock H = lock L, lock J = lock M, forebay lock J = forebay lock M) and the north – south orientation.

4.6 Effect of water level changes of lakes and water releases

The water levels and corresponding water volumes of Gatun Lake and Miraflores Lake form input for the simulation model. The effect of water releases from the lakes on the water volumes is implied in the water levels, which are prescribed in the input table. The effect of water level changes of the lakes on the salt concentration is evaluated at the start of each day in the simulation.

Water releases (spillage of surplus water through Gatun Spillway and Miraflores Spillway, water for power generation, water for cooling) are prescribed through the water-release scenarios. The effect of the water releases on the salt concentration of the lakes is evaluated in the simulation, at the moment of time when the water-release scenarios are executed.

For a description of the evaluation of the effects of water level changes and water releases on the salt concentration of the lakes, reference is made to Report A.

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 that will be used in the simulation model for the future situation are selected on the experiences with the existing situation and on Delft3D density-flow computations.

5.1 Exchange coefficients when wsb's are in use

5.1.1 Delft3D computations

We have executed Delft3D computations for the filling and emptying process in a lock chamber and for ship movements from one lock chamber to another.

In order to restrict the number of grid cells and thus to keep computation times below reasonable limits the computation of the filling and emptying process is done for a 15 m wide section of the lock chamber. The size of 15 m is selected because the fill openings in both lock chamber walls are placed at a center to center distance of 15 m; the 15 m wide section thus contains two openings (in the center line of the section). This section model is regarded as a representative model for the full lock chamber.

Lock chamber filling

A series of computations has been done aimed to simulate the filling process and the density currents in the lock chamber during filling. In these computations the initial water depth was 20 m and the final water depth 28.5 m. The lock chamber was filled in 15 minutes (900 s).
As an example, in one computation the initial salt concentration was 12 ppt at the floor and 8 ppt near the water surface (lineair decrease). The lock chamber was filled from three water saving basins, successively from lower, middle and upper basin with salt concentration 14 ppt, 16 ppt and 18 ppt respectively, each contributing 20% to the the total fill-water volume; the remaining 40% was supplied from the higher lock and had a salt concentration of 3 ppt (concentration values may be representative for filling of the lower lock chamber). This computation was repeated for the situation with the three individual wsb's replaced by a single one, with salt concentration of 16 ppt. The computed volume-averaged salt concentration of the lock chamber during filling is shown in Figure 5.1 for these two situations. The figure indicates that with three wsb's the salt concentration of the lock chamber increases slower and than more rapidly, but after filling the concentration is equal in both situations.
More important are the density-flow phenomena which occurred in the lock chamber in the computations, but these phenomena can not be read from the figure. These phenomena have been made visible by displaying the actual salt concentration distribution in the lock chamber at different moments of time as a series of consecutive 'snap shots'. This movie

demonstrates that the saltier water from the wsb's enters horizontally from both openings in the lock walls; in the center of the chamber (in between both lock walls) an upward movement develops but the saltier water spreads from the center to the sides, thus forming a lower layer with higher salt concentration (this process is governed by internal density flows, in particular in transverse direction of the lock chamber). The lower layer thickens and lifts the upper layer with initial lower salt concentration. Mixing up of the upper layer with the lower layer does hardly not occur in this phase. After filling with water from the wsb's, water with a lesser salt concentration is supplied from the higher lock. The movie shows that the inflowing water causes an upward water movement in the center of the lock chamber, at the location where the two jets meet. This upward flow is able to mix up the earlier formed upper and lower layer. As a result, the salt concentration becomes rather uniform at the end of filling (but the highest concentration is present near the floor).

In the case that the initial salt concentration of the lock chamber is ample higher than the salt concentration of the wsb (this may for example be the case after opening and subsequently closure of the gates at the seaside), the fill water from the wsb's will rise to the water surface and mix up the full water body of the lock chamber. Final mixing will than caused by the fill water from the adjacent higher lock. Again, the salt concentration in the lock chamber becomes rather uniform after filling.

When the new 3-lift locks are compared with the existing locks it appears that the vertical salt distribution in the new locks after filling is more or less similar to the distribution that occurs in the existing locks with a floor filling system. This is an important observation. But, transverse density flow phenomena may be stronger in the new locks because of the wall-filling system with horizontal inflow.
It appears also that the single wsb causes the same density-flow effects as the series of three separate wsb's. From this we conclude that the three wsb's can be replaced by a single wsb in the simulation model, provided that salt-exchange coefficients are well selected.

In the case that the Delft3D computation was repeated with a ship (draught 14 m, beam 54 m) in the lock chamber, the saltier water from the wsb's spread in the space under the ship. Subsequently, the inflow of less saline water from the higher lock caused a somewhat lesser mixing up than when no ship was present.

Lock chamber emptying

A series of Delft3D computations have been made aimed to simulate the emptying process of the lock chamber. The initial water depth was 28.5 m and the final water depth 20 m. The lock chamber was emptied in 15 minutes (60% of the water was spilled into the wsb's and 40% into the lower lock).
As an example, in one computation the initial salt concentration in the lock chamber was 18 ppt near the floor and 8 ppt near the water surface (lineair decrease). These concentration values may be representative for emptying of the lower lock chamber. The computed volume-averaged salt concentration of the lock chamber during emptying is shown in Figure 5.2. It appears that the decrease of the salt concentration is almost lineair. When we compute the quantity of salt that is transferred to successively upper wsb, intermediate wsb and lower wsb, we find that these quatities rather well correspond to the quantities of salt that were present in the respective lower water layers in the chamber. In other words: during emptying the water is hardly mixed up; the water is mainly drawn from the lower water area and the

vertical salt distribution in the remaining water volume does not change much. It also means that the upper wsb receives the water with highest salt concentration and the lower wsb the water with lowest salt concentration.
The density-flow phenomena have been made visible by means of a 'snap shot' movie. When emptying starts the water is drawn to the openings in both chamber walls. This process causes transverse, internal waves from the center of the chamber to the sides and back, but the vertical distribution of the salt concentration is not strongly effected. Apparently, the water is mainly drawn from the lower water area. This process is more or less similar as was earlier found for the existing locks with a floor emptying system, but the internal wave phenomena in transverse direction may be stronger.
The above computation was repeated with a ship (draught 14 m, beam 54 m) in the lock chamber. From the movie it appeared that the constraint space under the ship was the cause of a somewhat stronger mixing, in particular at the end of emptying.

Ship movement

Delft3D computations (2DV-approach) have been made of the exchange flows between two adjacent lock chambers when a density difference is present and a ship moves from the one lock chamber to the other. Dimensions of the ship: ship type VII, Post-Panamax, draught 14 m, see Section 3.4. The water depth in the lower chamber was 28.4 m, in the higher chamber 20.0 m. As an example we show the results for an uplocking ship (Figure 5.4) and a downlocking ship (Figure 5.5) for the case that the initial salt concentration is 12 ppt in the lower chamber and 3 ppt in the higher chamber (these concentration values may be representative for the lower and middle lock). The results for the salt exchange between the two lock chambers is also shown for the case that no ship is present (Figure 5.3). The three figures present the volume-averaged salt concentration in upper and lower chamber as a function of time.

The density-flow phenomena have been made visible by means of a 'snap-shot' movie. When no ship is present density flows develop fully between the two basins. The movie demonstrates that a salt tongue enters the upper chamber over the floor while simultaneously a tongue with lesser salinity and density enters the lower chamber near the water surface. The propagation velocity of the two fronts is about 0.5 m/s (but the salt tongue propagates at a somewhat lower speed than the tongue near the water surface). Both tongues reflect against the closed end of the respective lock chambers. Mainly the water body in the lower chamber above the level of the step, is involved in the exchange process. Figure 5.3 shows that the average salt concentration in both lock chambers becomes equal after a period of about 1400 s, but than deviate again due to the action of internal waves.

The computation with a Post-Panamax ship moving from lower chamber to upper chamber shows that the intrusion of salt water into the upper chamber is to a considerable extent prevented by the return current of the ship. From the movie it appears that most salt water enters the upper lock after the ship has entered. Figure 5.4 indeed indicates that the average salt concentration of the upper lock chamber remains more or less constant during movement of the ship. The salt concentration of the lower lock decreases during movement of the ship because of the return current with lesser salinity. The salt exchange coefficient e_x is also indicated in Figure 5.4 and is derived making use of the formula's of Section 4.2. As can be read e_x is a negative during movement of the ship and becomes positive (small value) at the end of the ship movement.

In the case that a ship moves from upper lock to lower lock the return current sustains the intrusion of salt water into the upper lock. Salt water from the lower lock is forced to flow into the upper lock, but the involved water originates for a great part from the water body above the level of the step. Figure 5.5 indicates that the average salt concentration of the upper lock increases when the ship moves to the lower lock, while the concentration of the lower lock remains more or less constant. The latter indicates that also some saltier water from the water body below the level of the step enters the upper lock. The exchange coefficient e_x shown in Figure 5.5, has been derived with the help of the formula's of Section 4.3, and is small at the end of the ship movement.

The described phenomena are similar to the phenomena that were observed during measurements in the existing locks on the Panama canal. For a detailed description reference is made to Report A.

5.1.2 Selection of exchange coefficients

The hydraulic phenomena in the 3-lift locks of the new lane have a strong resemblance with the phenomena in the existing 3-lift locks at the Atlantic side of the canal. The conditions in the locks during movement of an uplocking or downlocking ship are more or less similar. Filling and emptying of a lock chamber through the openings in the chamber walls cause stronger internal movements in transverse direction of the chamber, but the vertical salinity profiles change more or less in the same way as in the existing locks with floor filling and emptying system. Also the location of the intakes and outlets in forebays and tailbays are more or less similar. The main difference is caused by the action of the water saving basins: during emptying of a lock chamber the saltier water near the floor is transferred to the water saving basins and is returned when the chamber is filled again.

On the basis of the results of the Delft3D computations and the insights obtained in the hydraulic processes, we select equal exchange coefficients for step II (movement of ship) as applied for the existing 3-lift locks at the Atlantic side, both for the new locks at the Pacific side and the Atlantic side. In the existing situation the gates of the lower lock at the Pacific side are opened far before the ship, coming from the sea, enters the lock chamber. This is done to prevent disturbing cross currents between the tailbays of west and east lane (see Report A for background information). The new locks will have separate entrance channels; we therefore assume that cross currents in the tailbays caused by density flows are less important or negligable. For that reason we also assume that the gates of the new, lower lock at the Pacific side will be opened just before movement of the uplocking ship, similar as in the existing lower locks at the Atlantic side. Salt exchange coefficients of the existing lower locks at the Atlantic side (movement of ship) are therefore selected for the new lower locks at both sides of the canal.

Taking into account the results of the D3D computations the exchange coefficients used for step I 'equalize water levels' are selected as:

uplockage
fill wsb of high lock: $e_{fillwsb} = 1.35$
empty wsb of low lock: $e_{emptywsb} = 1.0$
equalize water levels: $e_x = 1.25$ (for lock-forebay combination: 0.95)

downlockage

fill wsb of low lock: $e_{fillwsb}$ = 1.2
empty wsb of high lock: $e_{emptywsb}$ = 1.0
equalize water levels: e_x = 1.2 (for forebay-lock combination: 0.85)

The exchange coefficient 'equalize water levels' for the lock-forebay combination and the forebay-lock combination is equal to the corresponding coefficient for the existing situation. This coefficient is selected because of the similarity of forebay lay out and location of water intakes.

An overview of selected exchange coefficients for the locks at the Pacific side is presented in next tables.

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*
Forebay Lock J	Gatun Lake	(Density flows)	1.0**

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

Table 5.1 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	1.0**
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*

*) 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 5.2 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb.

Equal exchange coefficients are selected for the locks at the Atlantic side.

5.2 Exchange coefficients when wsb's are not in use

In the case that the wsb's of the new locks are not in use the hydraulic phenomena in the 3-lift locks in the new lane are very similar to the phenomena in the existing 3-lift locks at the Atlantic side (filling and emptying of the lock chambers from both sides result in more or less equal vertical salinity profiles, but stronger internal transverse waves). For that reason similar exchange coefficients are selected both for the new locks at the Pacific side and the Atlantic side (we assume that the lower lock at the Pacific side is operated in the same way as the lower lock at the Atlantic side; see report A for more background information).

An overview of selected exchange coefficients for the locks at the Pacific side is presented in next tables.

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*
Forebay Lock J	Gatun Lake	(Density flows)	1.0**

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

Table 5.3 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	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	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*

*) 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 5.4 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks without wsb.

Equal exchange coefficients are selected for the locks at the Atlantic side.

5.3 Other exchange coefficients

The exchange coefficients for the locks in the existing shipping lanes do not change after opening of the new, third shipping lane (for values of the exchange coefficients reference is made to Report A).

We also assume that the exchange coefficients related to the release of water at Gatun Dam and Miraflores are uneffected by the new shipping lane. The values of these exchange coefficients have been selected on the basis of validation runs for the existing situation (see report A). Maintaining equal exchange coefficients for the release of water offers also the possibility of a direct analysis of the third-lane related inflow of salt water into the lakes.

6 Testing of simulation model

The salt-intrusion simulation model of the existing situation has been extended with the three-lift locks in the new lane. The extension required the adaptation of formula in view of the water saving basins of the new locks, the definition of extra scenarios for ship movements and turn arounds, the definition of new Post-Panamax ship types, 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.

Input data

Test cases were such designed that the functioning of in particular the new items could be checked. Next Day Patterns and Coefficient Sets were used in the test runs:

Day Pattern	*Scenarios in day Pattern*	*Lane*
d1	Ship movement Pac. → Atl.; ship type 0	New, third (3-lift locks)
d2	Ship movement Atl. → Pac.; ship type 0	New, third (3-lift locks)
d3	Ship movement Pac. → Atl.; ship type VIII	New, third (3-lift locks)
d4	Ship movement Atl. → Pac.; ship type VIII	New, third (3-lift locks)
d5	Ship movement Pac. → Atl.; ship type VII	New, third (3-lift locks + wsb's)
d6	Ship movement Atl. → Pac.; ship type VII	New, third (3-lift locks + wsb's)
d7	Gatun Spillway; daily discharge = 5.10^6 m^3 Gatun Power Station; daily discharge = 5.10^6 m^3 Mirflaores Spillway (+cooling) ; daily discharge = 5.10^4 m^3	-
d8	Ship movement Pac. → Atl.; ship type VI	New, third (3-lift locks)
d9	Ship movement Atl. → Pac.; ship type VI	New, third (3-lift locks)
d10	Ship movement Pac. → Atl.; ship type V	New, third (3-lift locks)
d11	Ship movement Atl. → Pac.; ship type V	New, third (3-lift locks)
d12	Ship movement Pac. → Atl.; ship type IV	New, third (3-lift locks + wsb's)
d13	Ship movement Atl. → Pac.; ship type IV	New, third (3-lift locks + wsb's)
d14	Ship movement Pac. → Atl.; ship type III Ship movement Pac. → Atl.; ship type VIII Ship movement Pac. → Atl.; ship type VIII	West + East New, third (3-lift locks) New, third (3-lift locks + wsb)
d15	Ship movement Atl. → Pac.; ship type III Ship movement Atl. → Pac.; ship type VIII Ship movement Atl. → Pac.; ship type VIII	West + East New, third (3-lift locks) New, third (3-lift locks + wsb)

Table 6.1 Overview of Day Patterns used in test cases

Coefficient Set	*Up equalize*	*Up ship*	*Down equalize*	*Down ship*	*Up fill*	*Up empty*	*Down fill*	*Down empty*	*Exchange with lakes*	*Water releases*
c1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
c2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
c3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
c4	0.1	0.3	0.5	0.7	0.2	0.4	0.6	0..8	1.0	1.0
c5	0.5	0.2	0.5	0.2	0.5	1.0	0.5	1.0	1.0	1.0

Table 6.2 Overview of Coefficient Sets used in test cases

Test series A

A first series of tests was done with the salt concentration of all basins (including Pacific and Atlantic tailbays) set on 0. The purpose of these tests was to check the handling of water levels, water volumes, water displacement of new ship types and the set up of the water balance when a ship moves from ocean to ocean. The results of the water-balance computations have been checked by computations 'by hand'.
An overwiew of test cases of test series A is presented in Table 6.3.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
1	c1	d1	Jan 1 – Jan 31, 1970	scenario	single ship, S = 0
1-R	c1	d2	Jan 1 – Jan 31, 1970	scenario	single ship, S = 0
2A	c1	d3	Jan 1 – Jan 31, 1970	scenario	single ship, S = 285000
2A-R	c1	d4	Jan 1 – Jan 31, 1970	scenario	single ship, S = 285000
3A	c1	d5	Jan 1 – Jan 31, 1970	scenario	single ship, S = 260000
3A-R	c1	d6	Jan 1 – Jan 31, 1970	scenario	single ship, S = 260000

Table 6.3 Test cases series A: initial salt concentration is zero in all basins

Conclusions test series A

Water levels and water volumes, also those of the new basins in the simulation model, are well computed. Water transfer in the existing locks, new locks and wsb's caused by uplocking and downlocking ships is correct simulated and the water quantities fulfil the water balance.

Test series B

The set up of water balance and salt balance, the use of exchange coefficients, the time-dependent exchange of salt water between forebays and lakes, the proper functioning of spillways and the salt-water migration process from the lakes downwards has been checked in test series B. The initial salt concentration of Miraflores Lake and Gatun Lake was set on 30 ppt, the initial salt concentration of all other basins was set on 0.
An overwiew of test cases of test series B is presented in Table 6.4.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
4	c2	d7	Jan 1 – Dec 31, 1970	day	water releases
5A	c3	d1	Jan 1 – Jan 5, 1970	scenario	single ship, S = 0
5A-R	c3	d2	Jan 1 – Jan 5, 1970	scenario	single ship, S = 0
5B	c3	d8	Jan 1 – Jan 5, 1970	scenario	single ship, S = 200000
5B-R	c3	d9	Jan 1 – Jan 5, 1970	scenario	single ship, S = 200000
6	c4	d10	Jan 1 – Jan 5, 1970	scenario	single ship, S = 145000
6-R	c4	d11	Jan 1 – Jan 5, 1970	scenario	single ship, S = 145000
7	c4	d12	Jan 1 – Jan 5, 1970	scenario	single ship, S = 120000
7-R	c4	d13	Jan 1 – Jan 5, 1970	scenario	single ship, S = 120000
8	c5	d14	Jan 1 – Jan 5, 1970	scenario	several ships / all lanes
8-R	c5	d15	Jan 1 – Jan 5, 1970	scenario	several ships / all lanes

Table 6.4 Test cases series B: initial salt concentration of Gatun Lake and Miraflores Lake = 30 ppt, initial salt concentration of all other basins = 0

Conclusion test series B

The water balance and salt balance are well computed: salt water migrates properly from the lakes to all lower basins and to wsb's, the time-dependent exchange of salt water between forebays / tailbays and lakes is correct, the loss of salt water through water releases at Gatun Dam and Miraflores is well computed. Some results of Test case 8 are shown in Figures TC8, 1 – TC8, 8 as an example.

Test series C

In this third series of test cases the salt concentration of the tailbays at the Pacific and Atlantic side was set on 30 ppt. The aim of the tests was to check the salt-water intrusion from the seas into the lakes.

An overwiew of test cases of test series C is presented in Table 6.5.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
9	c5	d3	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
10-R	c5	d6	Jan 1 – Jan 5, 1970	scenario	single ship, S = 260000

Table 6.5 Test cases series C: initial salt concentration of Pacific and Atlantic tailbays = 30 ppt, initial salt concentration of all other basins = 0

Conclusion test series C

The water balance and salt balance are well computed: salt water migrates properly from the tailbays in the sea entrances to all higher basins and to wsb's, the time-dependent exchange of salt water between forebays / tailbays and lakes is correct.

As a last test the validation case for the existing situation (Case VAL1, see Report A) has been run as Case A-1 with the extended simulation model. The extended model produced fully identical results, see Figures A-1, 1 and A-1, 2.

7 Salt water intrusion analysis future situation

In this section we present the results of the salt-water intrusion analysis for the future situation with a new, third shipping lane. Three-lift Post-Panamax locks are built at both ends of the new lane. The locks are provided with water saving basins (wsb's, see also Section 2). In the analysis we make a distinction between the situation that wsb's are not in use and the situation that the wsb's are used to prevent the loss of water from Gatun Lake. A comparison with the present salt-water intrusion through the existing locks concludes the analysis.
Starting point for the analysis is that the water levels in Miraflores Lake and Gatun Lake vary throughout the year as in the existing situation. In the baseline scenario the water releases (through Gatun Spillway, Gatun Power Station, Miraflores Spillway, Miraflores Cooling Water Offtake) remain as they are in the existing situation (which means that additional water is supplied to Gatun Lake to compensate for the extra losses via the new locks). In the second scenario the water releases at Gatun Dam are reduced with the water losses caused by shipping in the new lane. In the case that these water losses are greater than the water releases (this will in particular occur in the dry season) we assume that additional water supplies are available to replenish the surplus losses. The ship transit prospects for the next 50 years as given by ACP are used.

7.1 Data used in numerical simulations

The next data is applied in the numerical simulations:

- Dimensions of locks, forebays, tailbays, water saving basins: the dimensions presented in Section 3.7 are selected.
- Water levels and salt concentrations of seaside tailbays: values presented in Section 3.9 are selected.
- Water levels and corresponding water volumes, water releases of Miraflores Lake and Gatun Lake: values presented in Section 3.8 are selected.
- Initialization data: see Section 3.10
- Exchange coefficients: see Chapter 5.

7.2 Set up of cases for simulation of the future situation

We assume that the new lane will come in operation at January 1, 2011. The present salt concentrations in Gatun Lake, Miraflores Lake and the locks on the existing shipping lanes are selected as initial salt concentrations. These salt concentrations have been obtained through numerical simulation of the salt water intrusion during the preceding year 2010. The initial salt concentrations in the new locks and wsb's are set to the values of the existing locks. This is not conform the real situation, but as can be seen from the computational results the salinity values in the new locks and wsb's grow fast to an equilibrium value.

The salt intrusion in the future situation is analysed for a period of 1 month, 1 year, 5, 10, 20 and 50 years after opening of the third lane. Various cases have been set up to simulate the salt intrusion during these periods. Day patterns which are applied in the various cases, are such defined that they reflect the development of the ship traffic intensities in the next 50 years. In next table the daily number of transiting ships and the type of ships are presented for the various consecutive time periods. Panamax vessels are represented by ship type III, regular ships by ship types I and II, Panamax-Plus vessels by ship type IV, Post-Panamax vessels by ship type VII (draught 14 m, during first 5 years after opening of the new lane) and ship type VIII (draught 15.2 m).

Period	*Jan 1, 2011 – Jan 31, 2011*	*Febr 1, 2011 – June 30, 2011*	*July 1, 2011 – Dec 31, 2011*	*Jan 1, 2012 – Dec 31, 2012*	*Jan 1, 2013 – Dec 31, 2015*	*Jan 1, 2016 – Dec 31, 2020*	*Jan 1, 2021 – Dec 31, 2025*	*Jan 1, 2026 – Dec 31, 2030*	*Jan 1, 2031 – Dec 31, 2040*	*Jan 1, 2041 – Dec 31, 2050*	*Jan 1, 2051 – Dec 31, 2060*
Vessel type	*Number of ships*										
Existing shipping lane West											
Type I	8	8	8	8	8	8	8	8	8	8	8
Type II	4	4	4	4	4	4	4	4	4	4	4
Type III	6	6	6	6	6	6	6	6	6	6	6
Total	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Existing shipping lane East											
Type I	8	8	8	8	8	8	8	8	8	8	8
Type II	4	4	4	4	4	4	4	4	4	4	4
Type III	6	6	6	6	6	6	6	6	6	6	6
Total	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Future third shipping lane (3-lift locks)											
Type IV	2	3	4	4	4	4	4	4	4	5	5
Type VII	0	0	1	2	0	0	0	0	0	0	0
Type VIII	0	0	0	0	2	3	4	5	7	9	10
Total	**2**	**3**	**5**	**6**	**6**	7	**8**	**9**	**11**	**14**	**15**
Simulations											
Period after opening of new lane	**1 month**	0.5 year	**1 year**	2 years	**5 years**	**10 years**	15 years	**20 years**	30 years	40 years	**50 years**

Table 7.1 Ship transits in simulation model in existing and new shipping lanes

In the set up of cases a distinction is made between 3-lift locks with wsb's, 3-lift locks without wsb's and 3-lift locks with and without wsb's and a reduced water release from

Gatun Lake, see Section 3.8 (water releases from Miraflores Lake remain as in the existing situation). The various cases are numbered as shown in Table 7.2.
In the baseline scenario we assume that all extra water losses caused by lock operation in the new shipping lane are compensated by extra water supplies to Gatun Lake, but water spills at Gatun Dam are not reduced. When the wsb's of the three-lift locks in the new lane are in use (Case B1) the extra water supply amounts to 2.10^5 m^3 water per transiting ship (leading to a water supply in year 50 of 3.10^6 m^3 per day). When the wsb's are not applied (Case B2) the extra water supply to Gatun Lake amounts to 5.10^5 m^3 water per transiting ship (leading to a water supply in year 50 of $7.5.10^6$ m^3 per day).
In the second scenario we assume that the water releases at Gatun Dam are reduced with the water losses caused by the new locks. Consequently, a lesser quantity of fresh water has to be supplied to Gatun Lake. In the dry season, however, the spilled quantities are small or nil and extra water supplies are still needed to compensate for the water losses of the new locks (see also Tables 3.18 and 3.19). When wsb's are used (Case B3) the water loss is 60% smaller than when they are out of use (case B4).
For reasons of comparison we have also simulated the salt water intrusion in the period 2011 – 2020 when no new shipping lane is realised. This case is indicated with A-10. The results for year 10 are in fact also valid for year 1, 5, 20 and 50, since these values are stable, equilibrium values for the given ship traffic intensity in the existing locks.

Simulation time	Existing Situation	Future Situation 3-lift locks **with** wsb's (baseline)	Future Situation 3-lift locks **without** wsb's	Future Situation 3-lift locks **with** wsb's and reduced water releases GL	Future Situation 3-lift locks **without** wsb's and reduced water releases GL
1 month		B1-1m	B2-1m		
1 year		B1-1	B2-1	B3-1	B4-1
5 years		B1-5	B2-5		
10 years	A-10	B1-10	B2-10	B3-10	B4-10
20 years		B1-20	B2-20	B3-20	B4-20
50 years		B1-50	B2-50	B3-50	B4-50

Table 7.2 Overview of cases

For the new shipping lane with alternative 2-lift locks or 1-lift locks we reserve the letters C and D respectively for designation of the cases.

7.3 Results of simulations and analysis

The computed salt concentrations (ppt) of Miraflores Lake and Gatun Lake in the period year 2016 – year 2020 (ending 10 years after opening of new lane) and the period year 2051 – year 2060 (ending 50 years after opening) are shown in Figures B1-10, 1 through B4-50, 2. The results for the existing situation (no new lane) for the period year 2011 – year 2020 are shown in Figures A-10, 1 and A-10, 2. As can be seen the salt concentrations of Miraflores Lake and Gatun Lake fluctuate as a function of wet and dry season; the salt concentration levels stabilize within a period of about 1- 2 years after a change in ship traffic intensity.

The maximum and minimum values of the salt concentration of Miraflores Lake and Gatun Lake in the last year of the considered period are presented in Table 7.3.

Case	*Considered year*	*Salt conc. (ppt) Miraflores Lake*		*Salt conc. (ppt) Gatun Lake*	
		minimum	*maximum*	*minimum*	*maximum*
A-10	10	0.64	1.42	0.010	0.027
B1-1month	-	0.65	0.99	0.009	0.011
B1-1	1	0.62	1.05	0.011	0.024
B1-5	5	0.63	1.49	0.012	0.032
B1-10	10	0.65	1.43	0.012	0.034
B1-20	20	0.66	1.53	0.013	0.036
B1-50	50	0.61	1.52	0.018	0.044
B2-1month	-	0.66	0.99	0.009	0.011
B2-1	1	0.62	1.05	0.009	0.025
B2-5	5	0.63	1.49	0.009	0.026
B2-10	10	0.64	1.42	0.009	0.026
B2-20	20	0.65	1.52	0.009	0.025
B2-50	50	0.61	1.51	0.009	0.026
B3-1	1	0.62	1.48	0.009	0.032
B3-10	10	0.65	1.43	0.015	0.039
B3-20	20	0.66	1.53	0.017	0.042
B3-50	50	0.62	1.53	0.025	0.057
B4-1	1	0.62	1.47	0.009	0.030
B4-10	10	0.65	1.43	0.016	0.035
B4-20	20	0.66	1.53	0.019	0.038
B4-50	50	0.62	1.53	0.032	0.046

Table 7.3 Maximum and minimum values of salt concentration of Miraflores Lake and Gatun Lake

The maximum and minimum values are also shown in Figures 7.1 (Miraflores Lake) and 7.2 (Gatun Lake). From Figure 7.1 it appears that the salt concentration of Miraflores Lake remains more or less as in the present situation (in all four cases B1-B4), but the salt concentration of Gatun Lake (Figure 7.2) changes. The increase of salt concentration is up to a factor 3.2 in year 50 for the most unfavourable case B4, but still the salinity level remains far below 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)).

It appears that Case B2 (no wsb's) is most favourable in view of salt-water intrusion (a small reduction of the salt concentration levels is predicted). This is caused by the large fresh-water supply to Gatun Lake. When wsb's are applied (Case B1) a 60% smaller fresh-water supply is required and we see that the salt concentration levels increase with a factor 1.7. The salt concentration levels increase further (factor 2 – 3) when the water releases at Gatun

Dam are reduced (Cases B3 and B4). Again, the computed salt concentration level of about maximum 0.06 ppt of Gatun Lake in year 50 is very low compared to fresh-water standards (see Figure 7.2a)

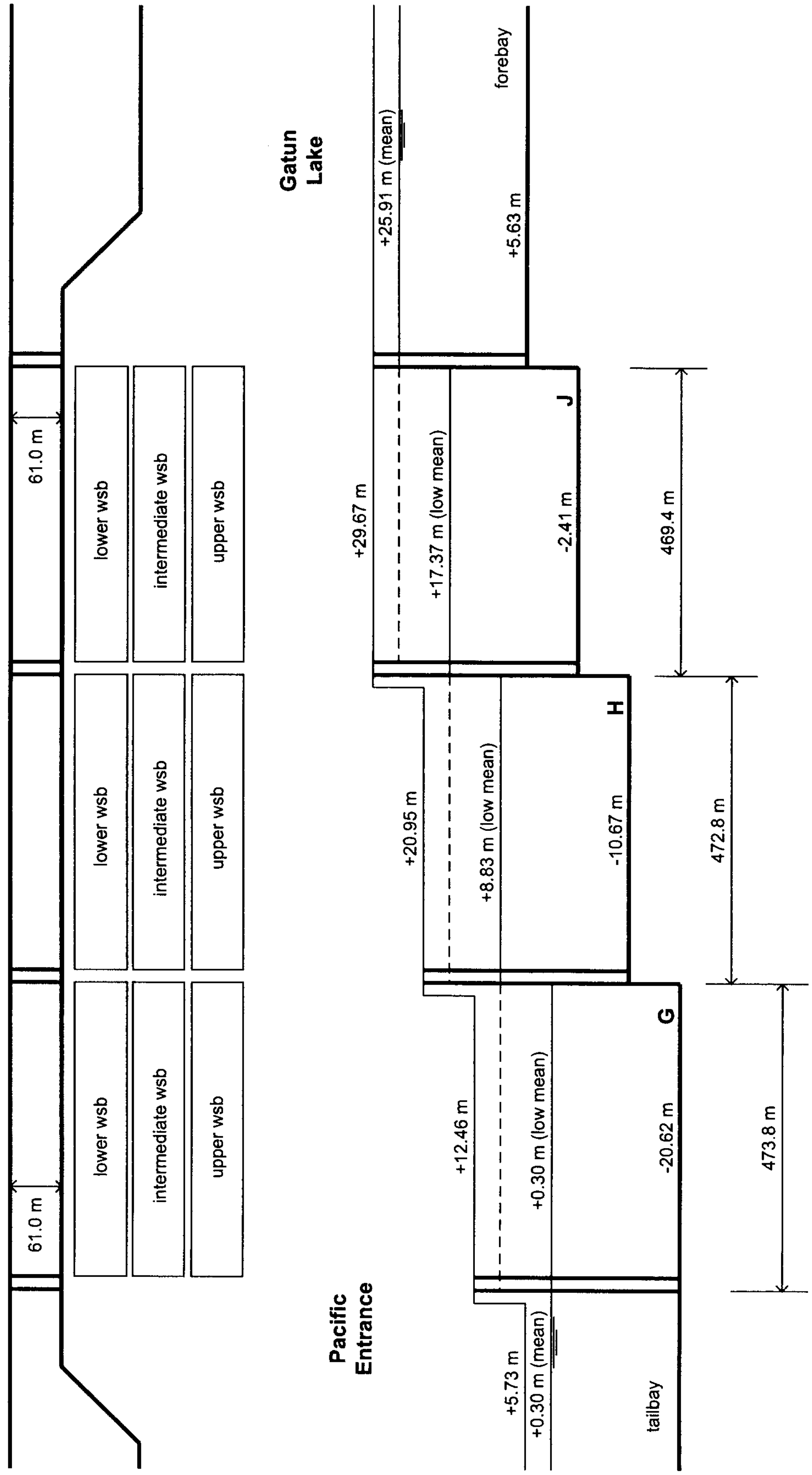
It should be noted that the computed concentration values are volume-averaged values, which means that local salt concentration values may be higher.

Conclusions

The main conclusions that can be drawn from the salt-water intrusion simulations are:

- The salt concentration of Miraflores Lake (Figure 7.1) is hardly effected by the new shipping lane (provided that the water releases at Miraflores Dam will be maintained).
- The volume-averaged salt concentration of Gatun Lake (Figures 7.2 / 7.2a) generally increases, in particular when wsb's are applied and water releases at Gatun Dam are reduced, but remains far below fresh-water limit values.

Figures

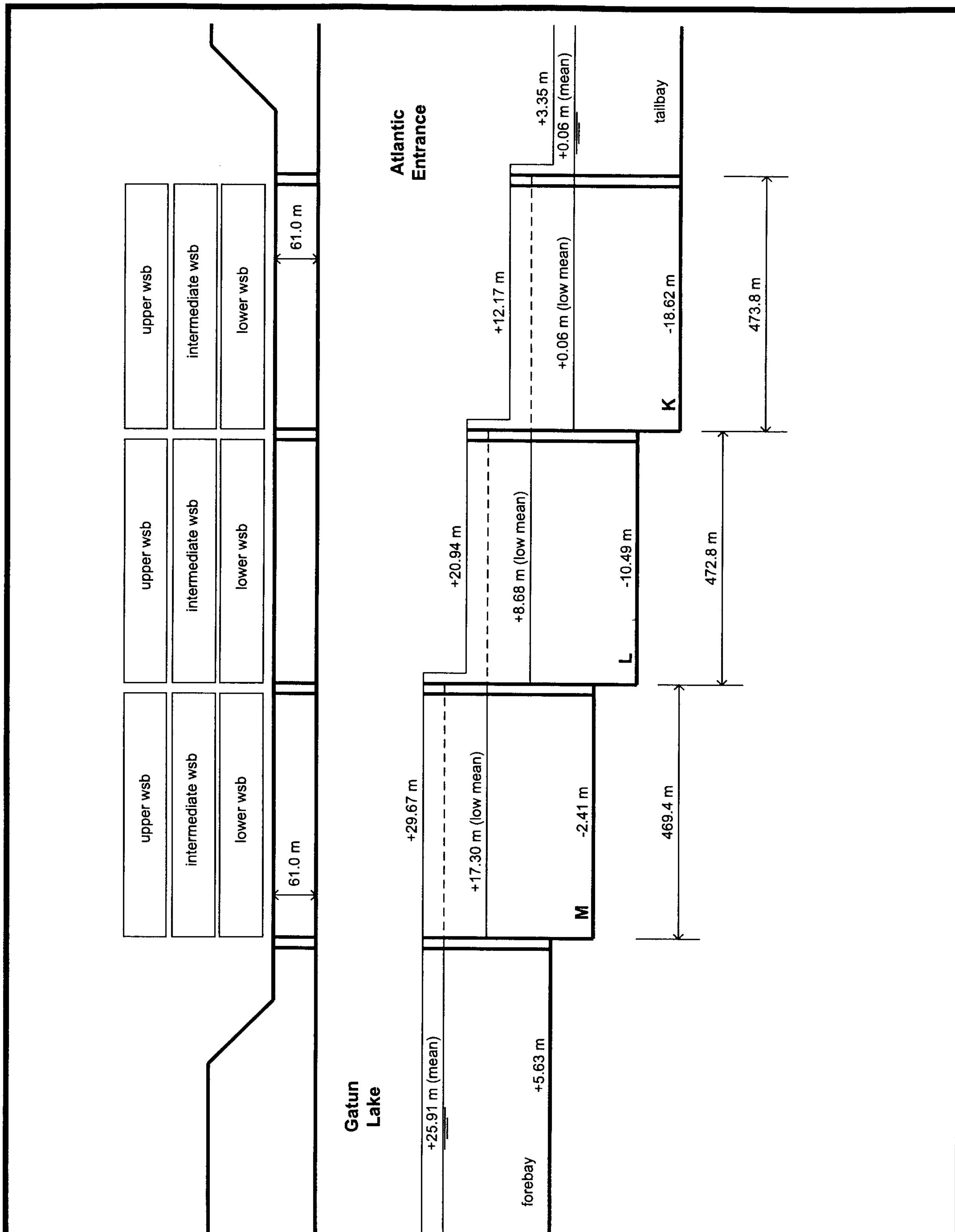


DESIGN OF 3-LIFT POST-PANAMAX LOCKS OF CPP
FOR PACIFIC SIDE, SHOWN SCHEMATICALLY

WL | DELFT HYDRAULICS

Q 3039

Fig. 2 .1

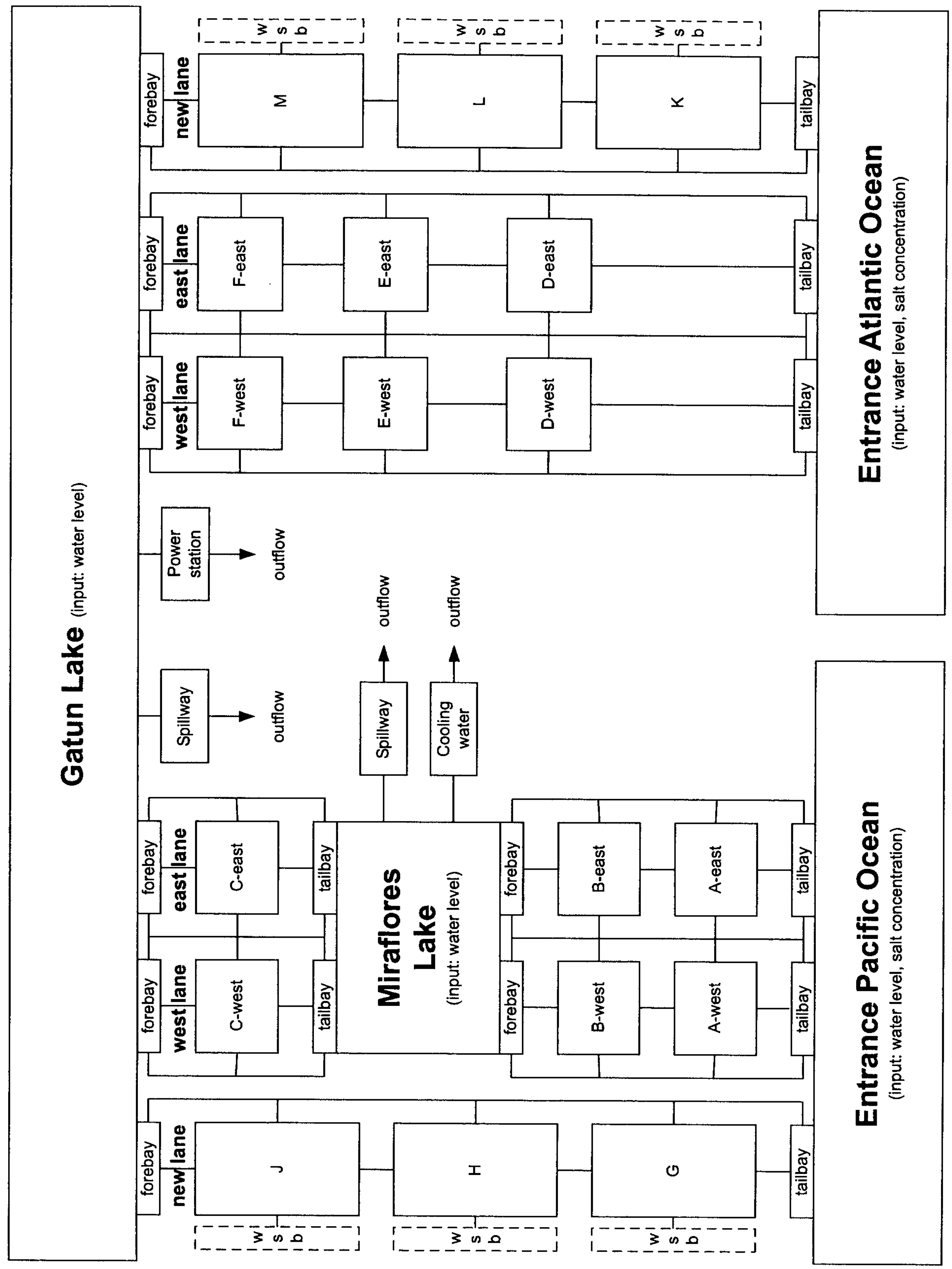


ASSUMED DESIGN OF 3-LIFT POST-PANAMAX LOCKS FOR ATLANTIC SIDE, SHOWN SCHEMATICALLY

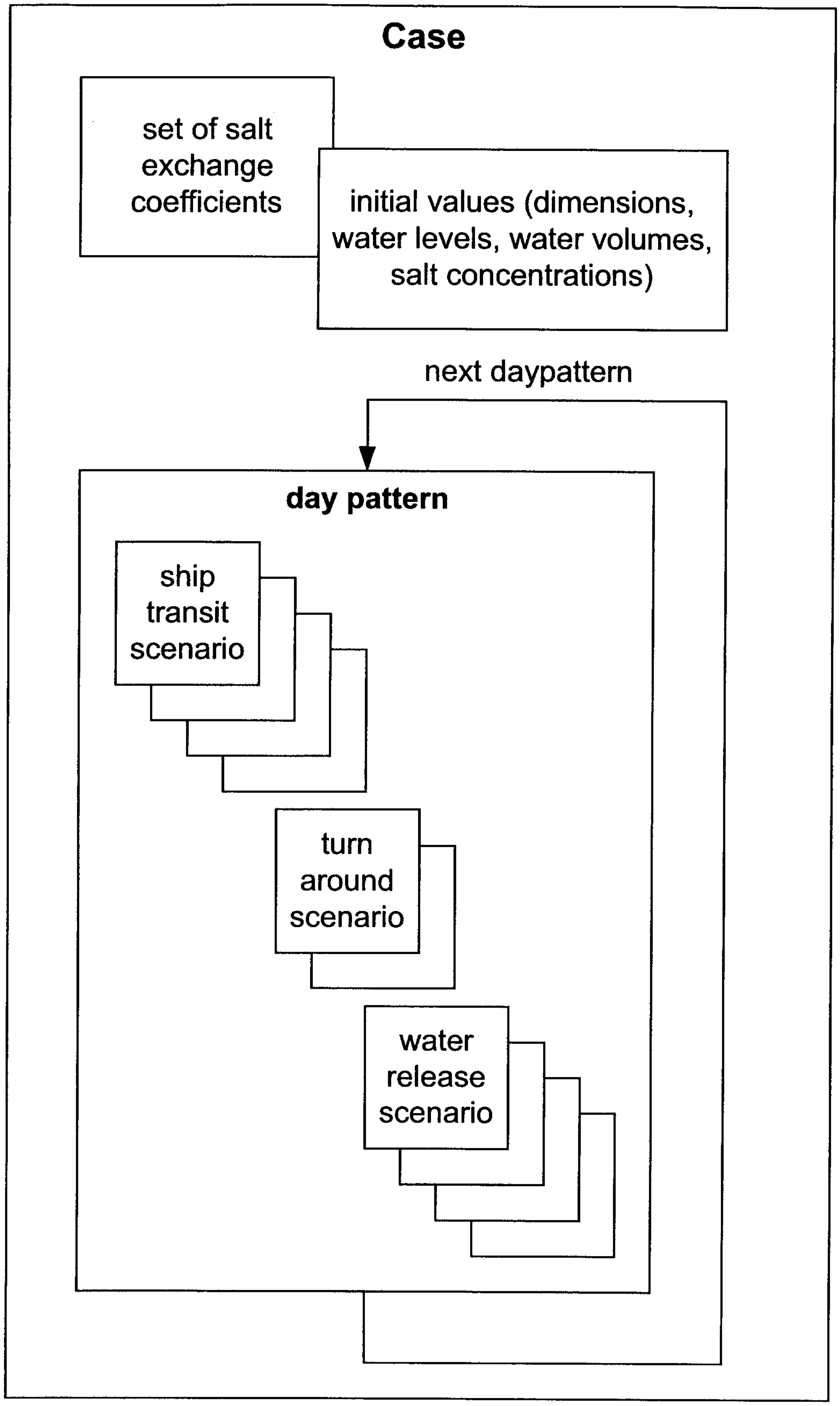
WL | DELFT HYDRAULICS

Q 3039

Fig. 2.2



SIMULATION MODEL WITH NEW LANE AND 3-LIFT LOCKS. NODES AND HYDRAULIC CONNECTIONS		
WL | DELFT HYDRAULICS	Q 3039	Fig. 3 .1

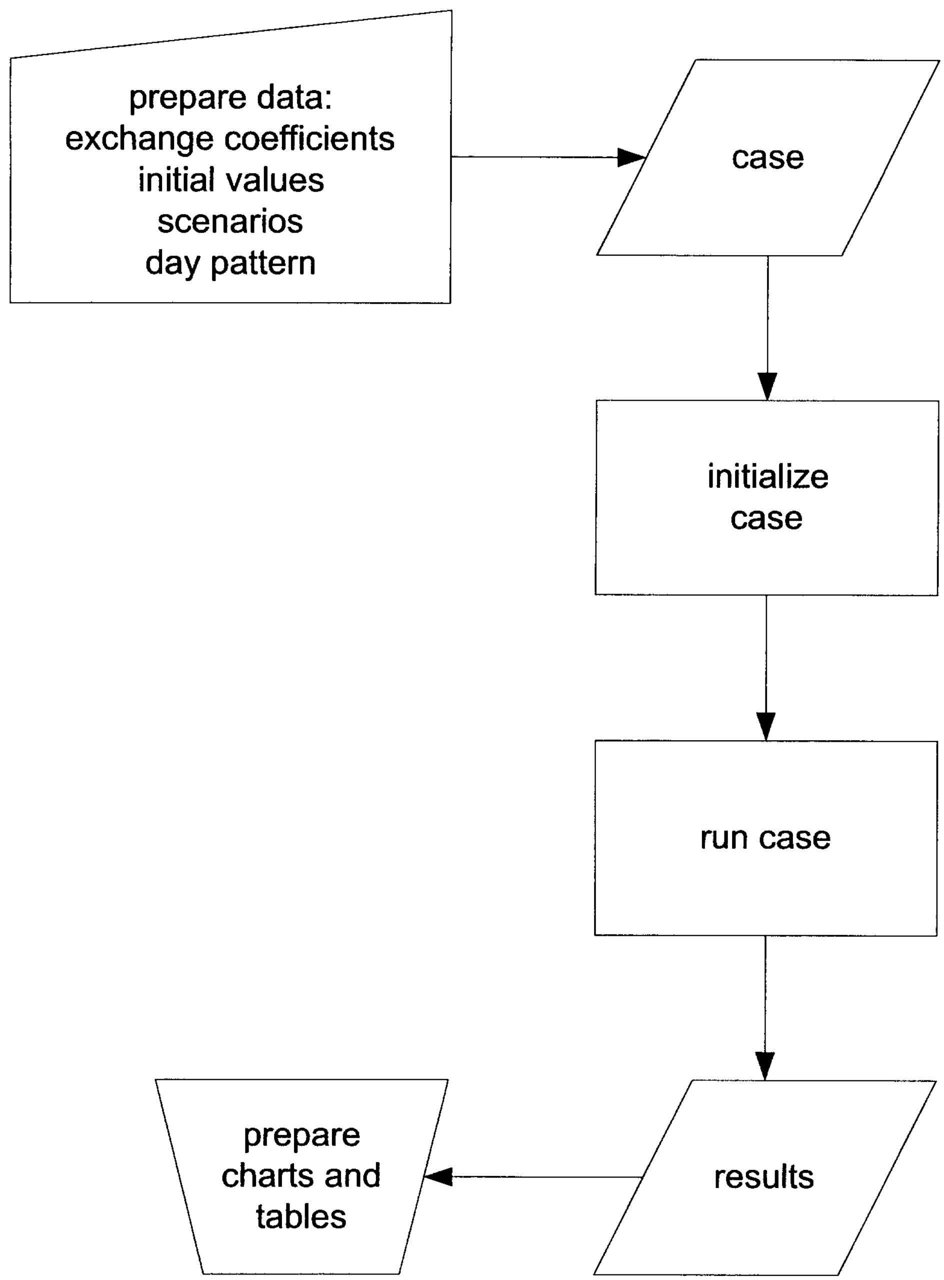


SIMULATION MODEL
COMPOSITION OF CASE

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.2

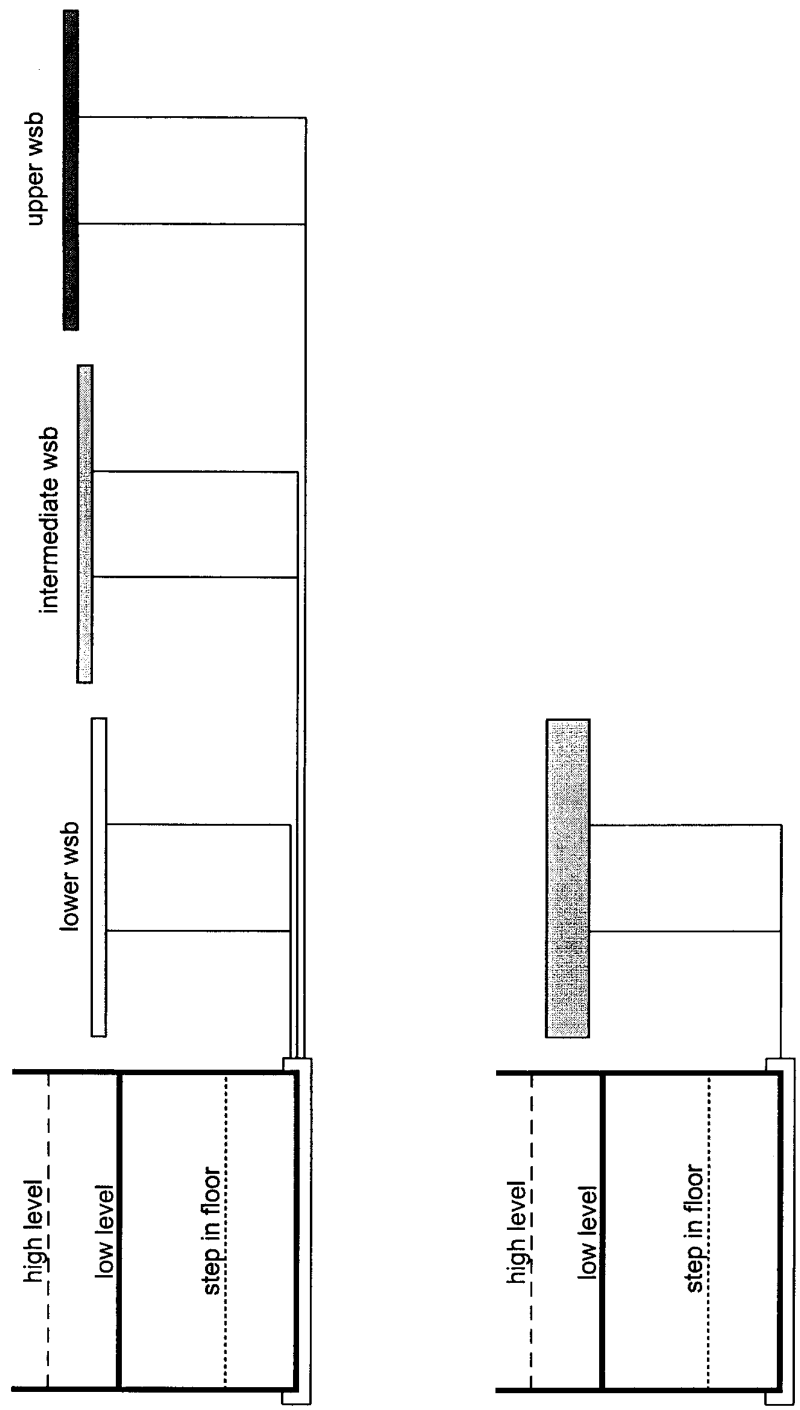


SIMULATION MODEL
FLOW CHART

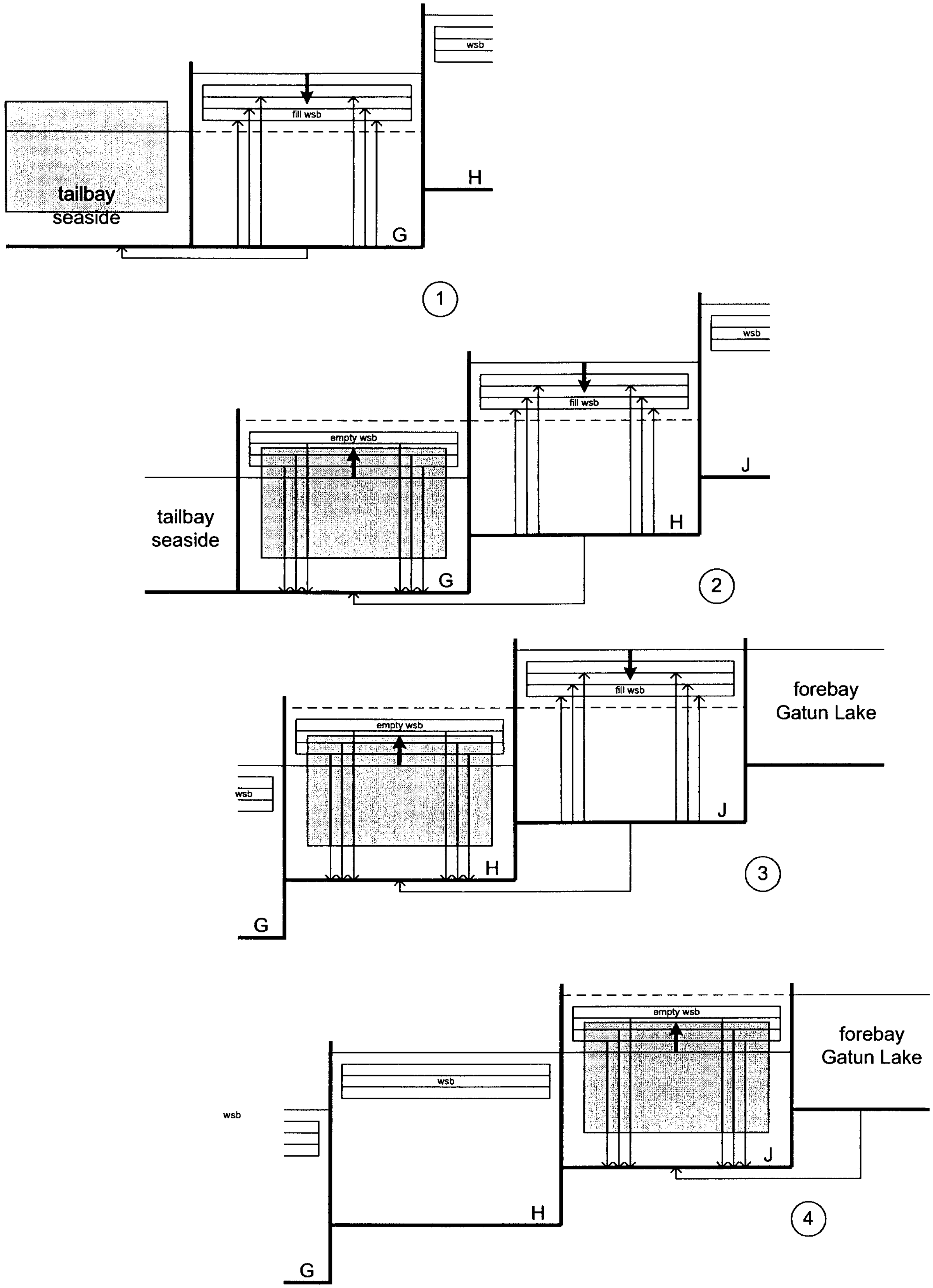
WL | DELFT HYDRAULICS

Q 3039

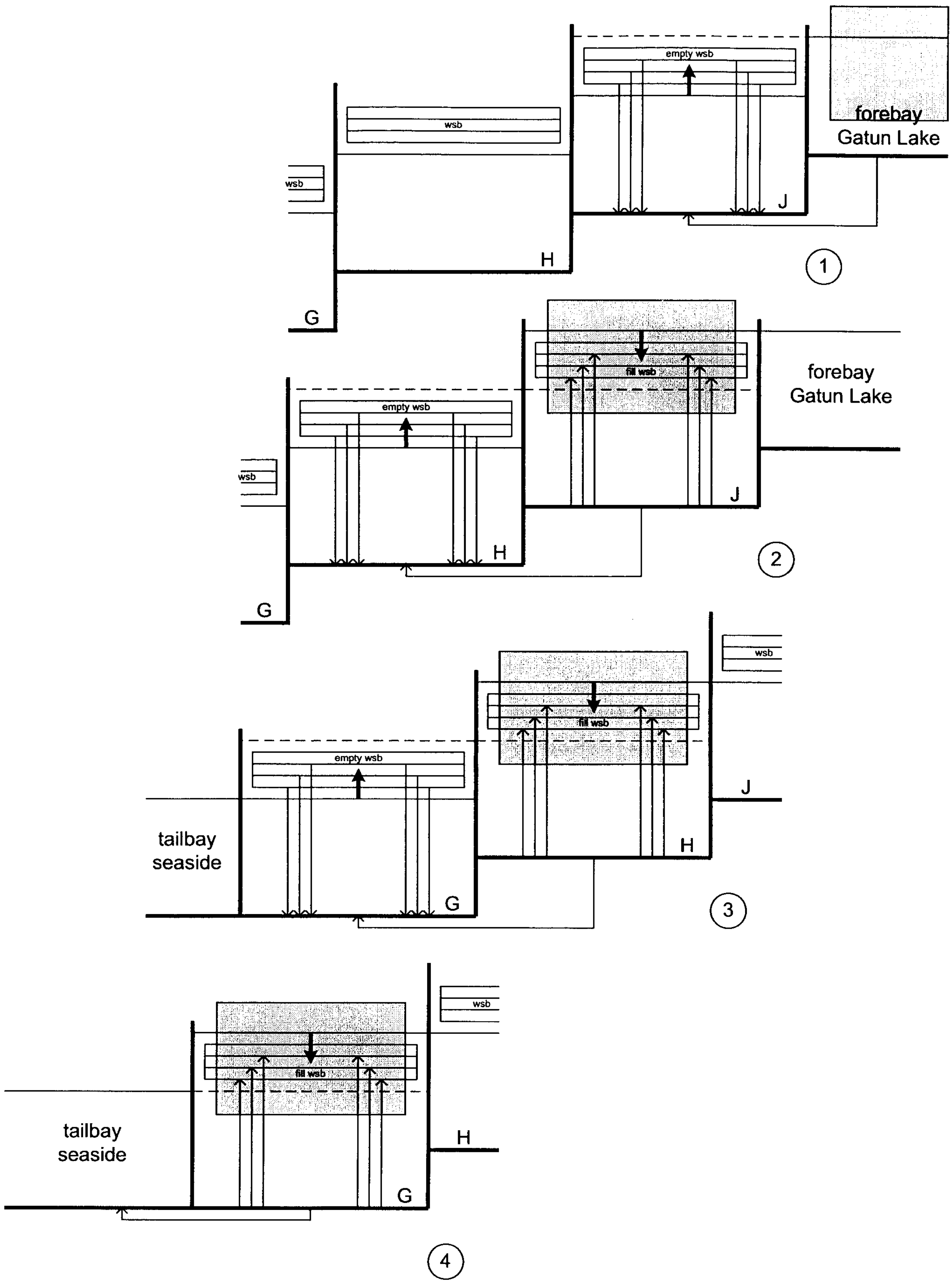
Fig. 3.3



REPRESENTATION OF LOCK WITH 3 WSB'S BY LOCK WITH SINGLE WSB		
	3-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.4



UPLOCKAGE FILLING AND EMPTYING OF WSB'S IN STEP I		
	3-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.5



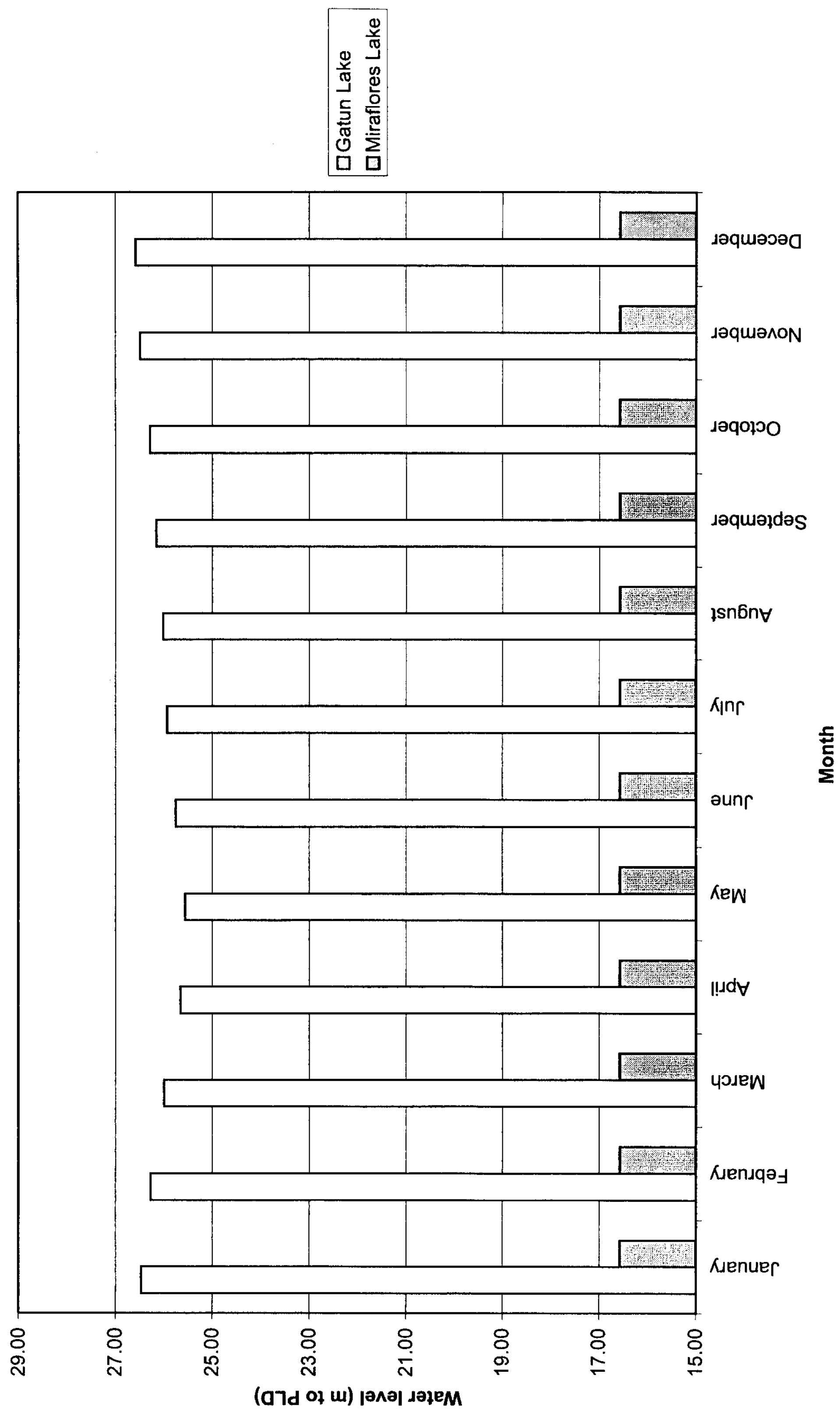
DOWNLOCKAGE
FILLING AND EMPTYING OF WSB'S IN STEP I

3-lift locks

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.6

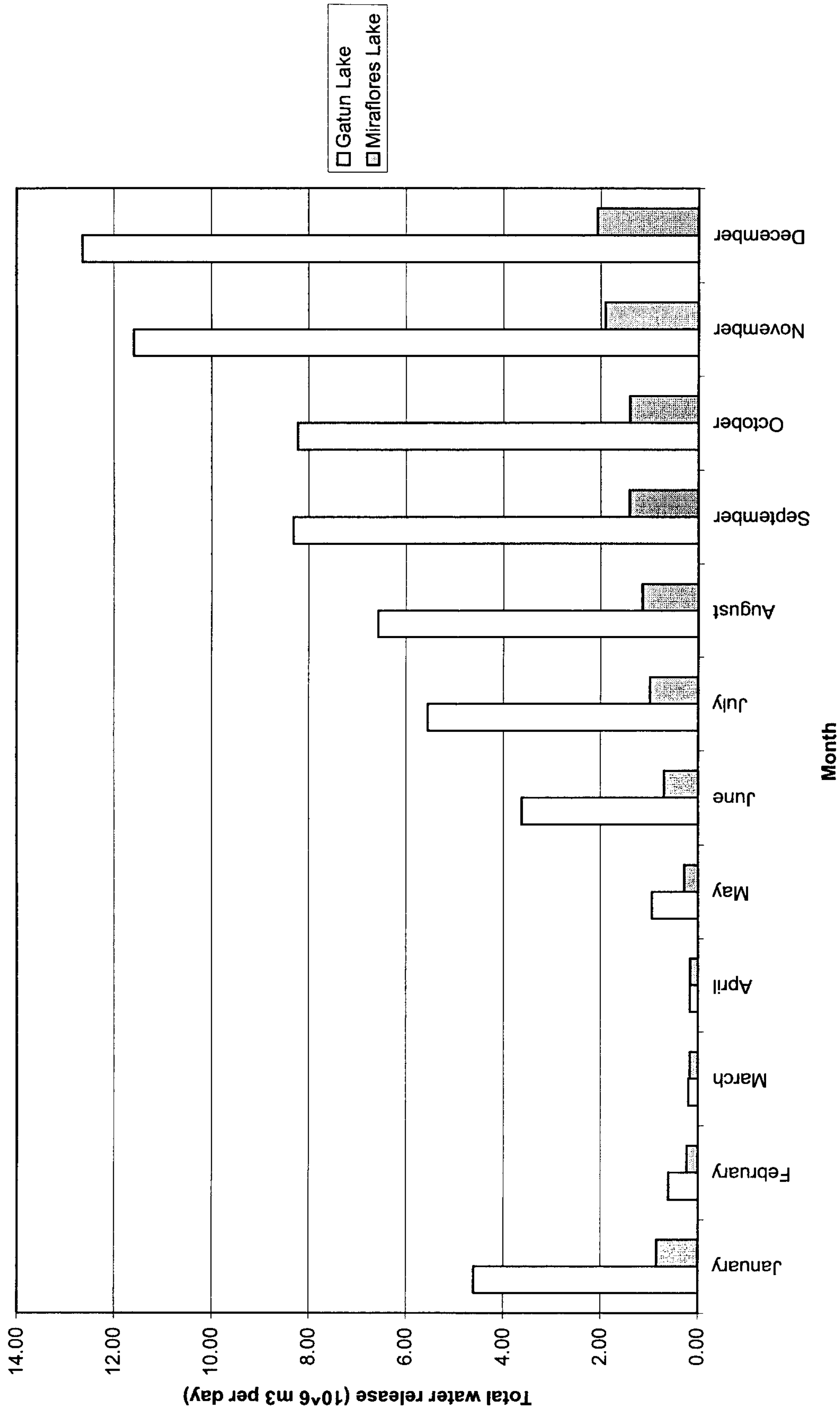


GATUN LAKE AND MIRAFLORES LAKE
REPRESENTATIVE WATER LEVELS

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.7

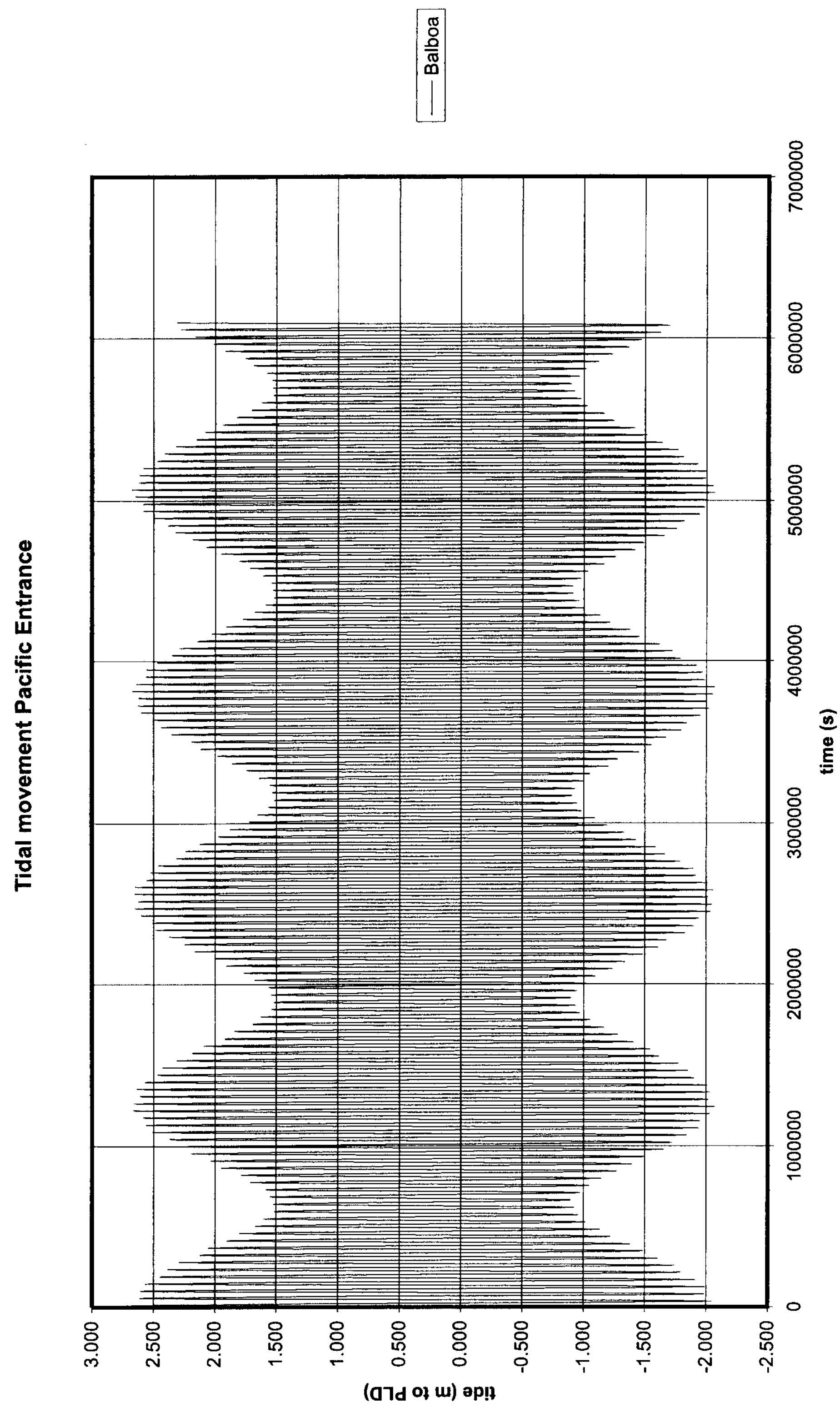


GATUN LAKE AND MIRAFLORES LAKE
WATER RELEASES (BASELINE SCENARIO)

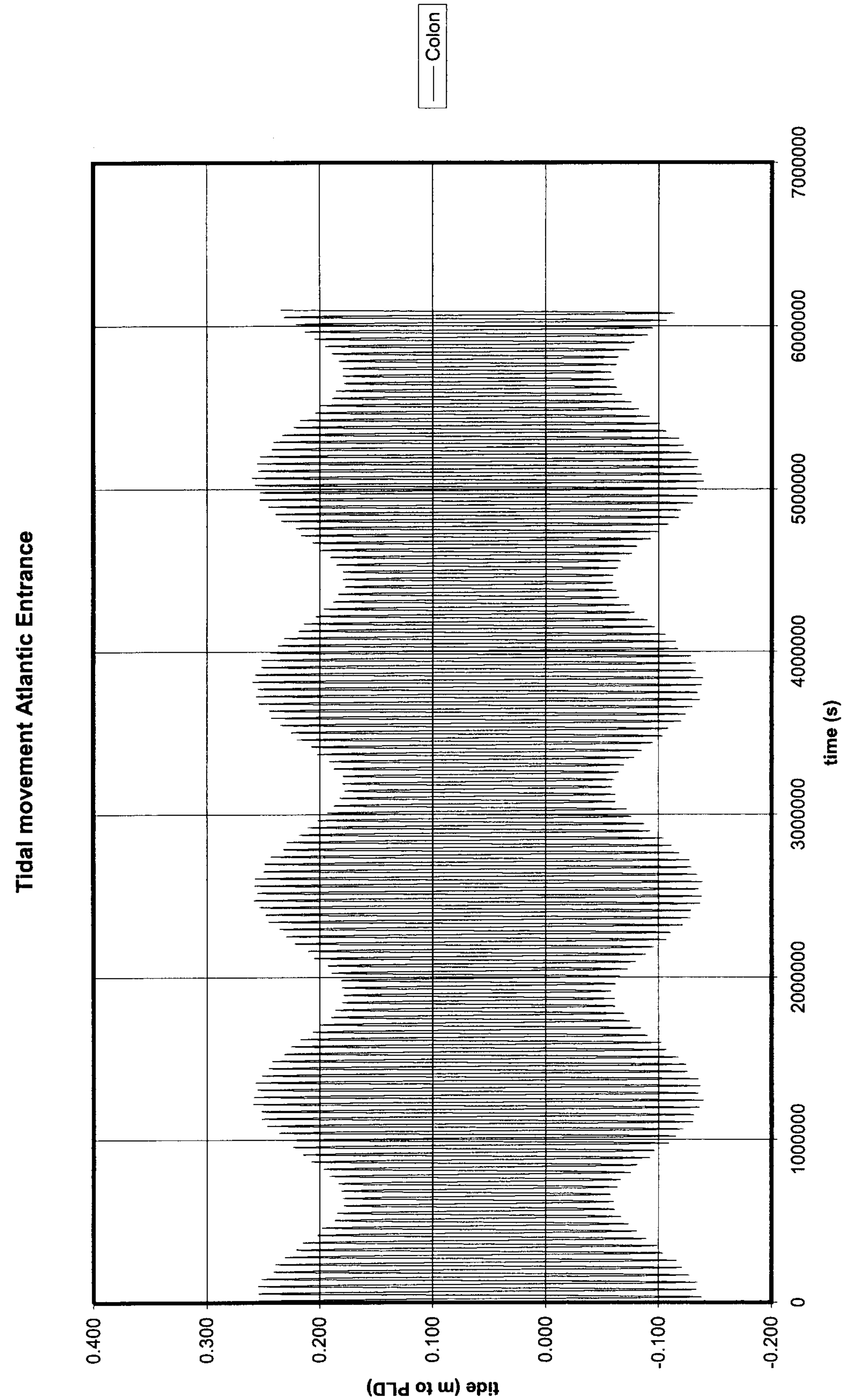
WL | DELFT HYDRAULICS

Q 3039

Fig. 3.8



TAILBAYS PACIFIC SIDE PREDICTION OF TIDAL MOVEMENT		
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.9

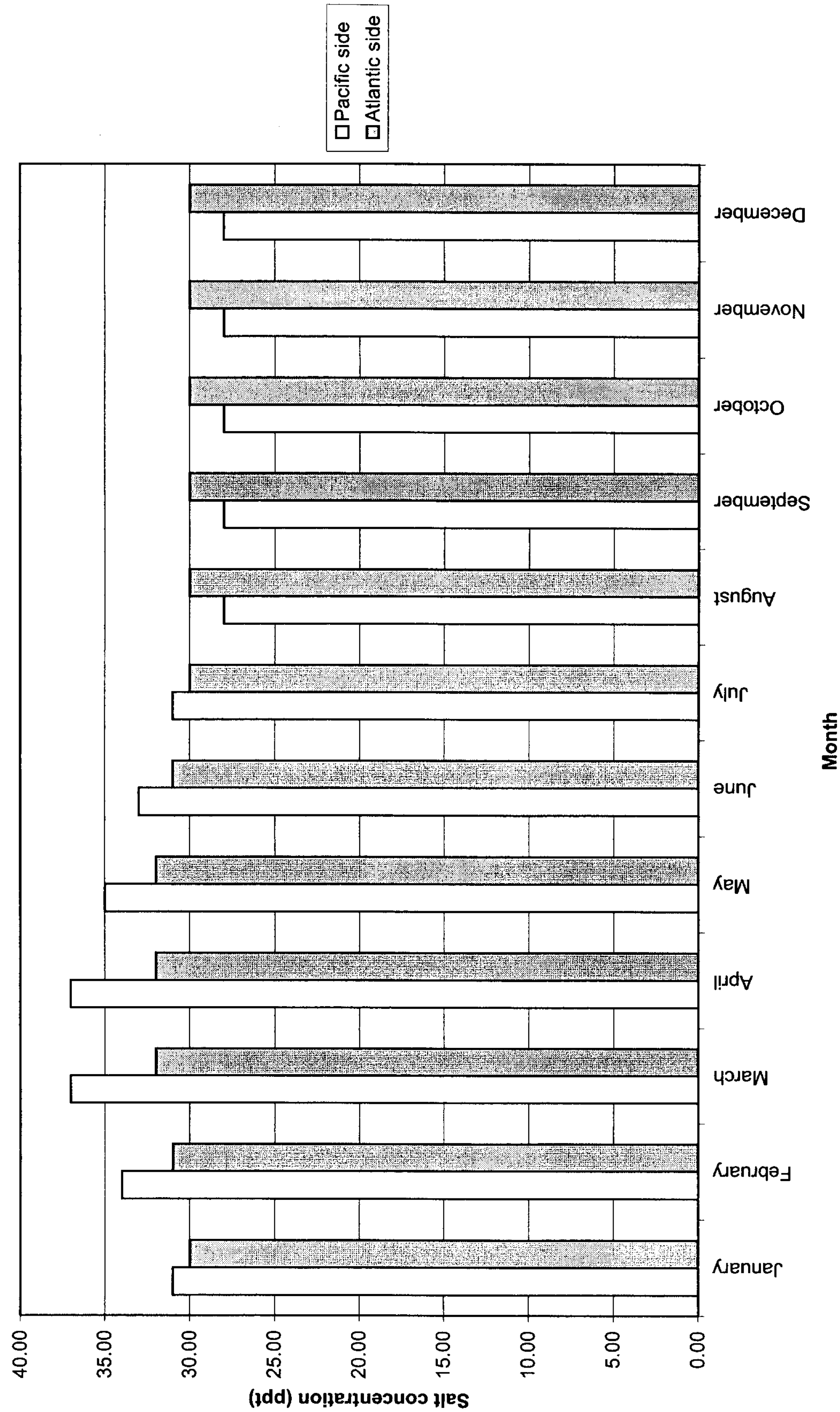


TAILBAYS ATLANTIC SIDE
PREDICTION OF TIDAL MOVEMENT

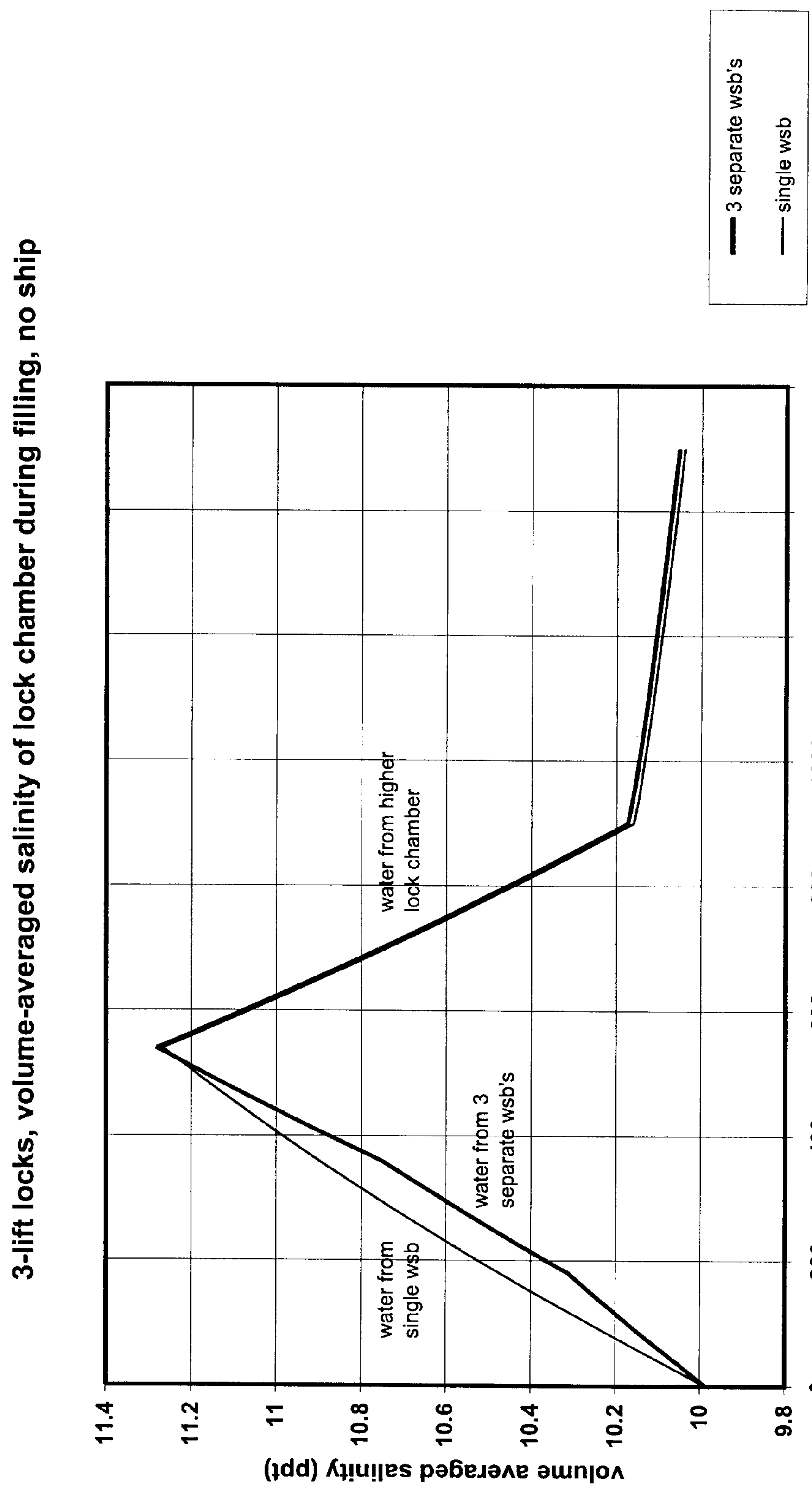
WL | DELFT HYDRAULICS

Q 3039

Fig. 3.10



TEMPERATURE-COMPENSATED SALT CONCENTRATION OF PACIFIC AND ATLANTIC ENTRANCES		
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.11

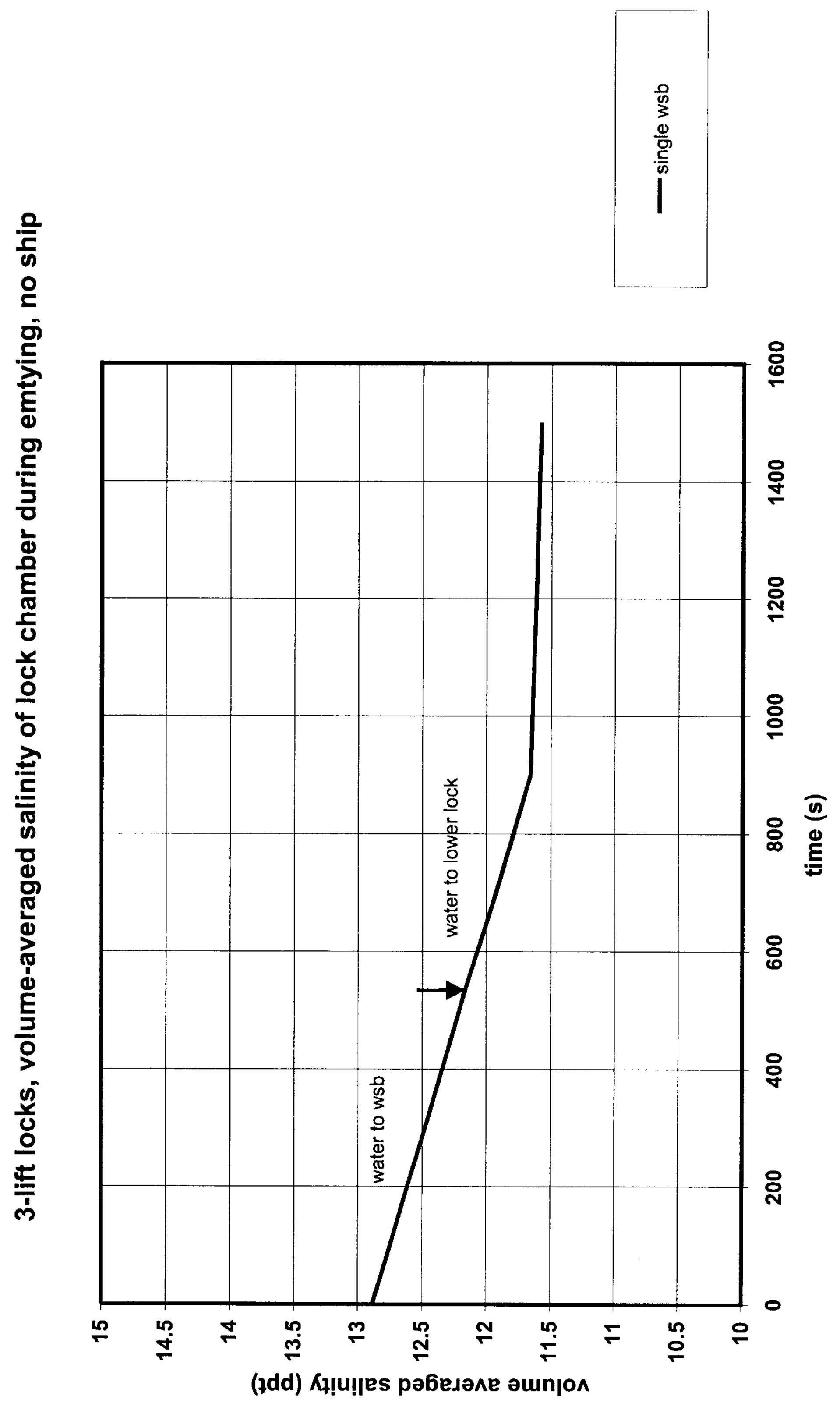


RESULTS OF DELFT3D COMPUTATION
VOL-AVERAGED SALINITY OF LOCK, FILLING, NO SHIP

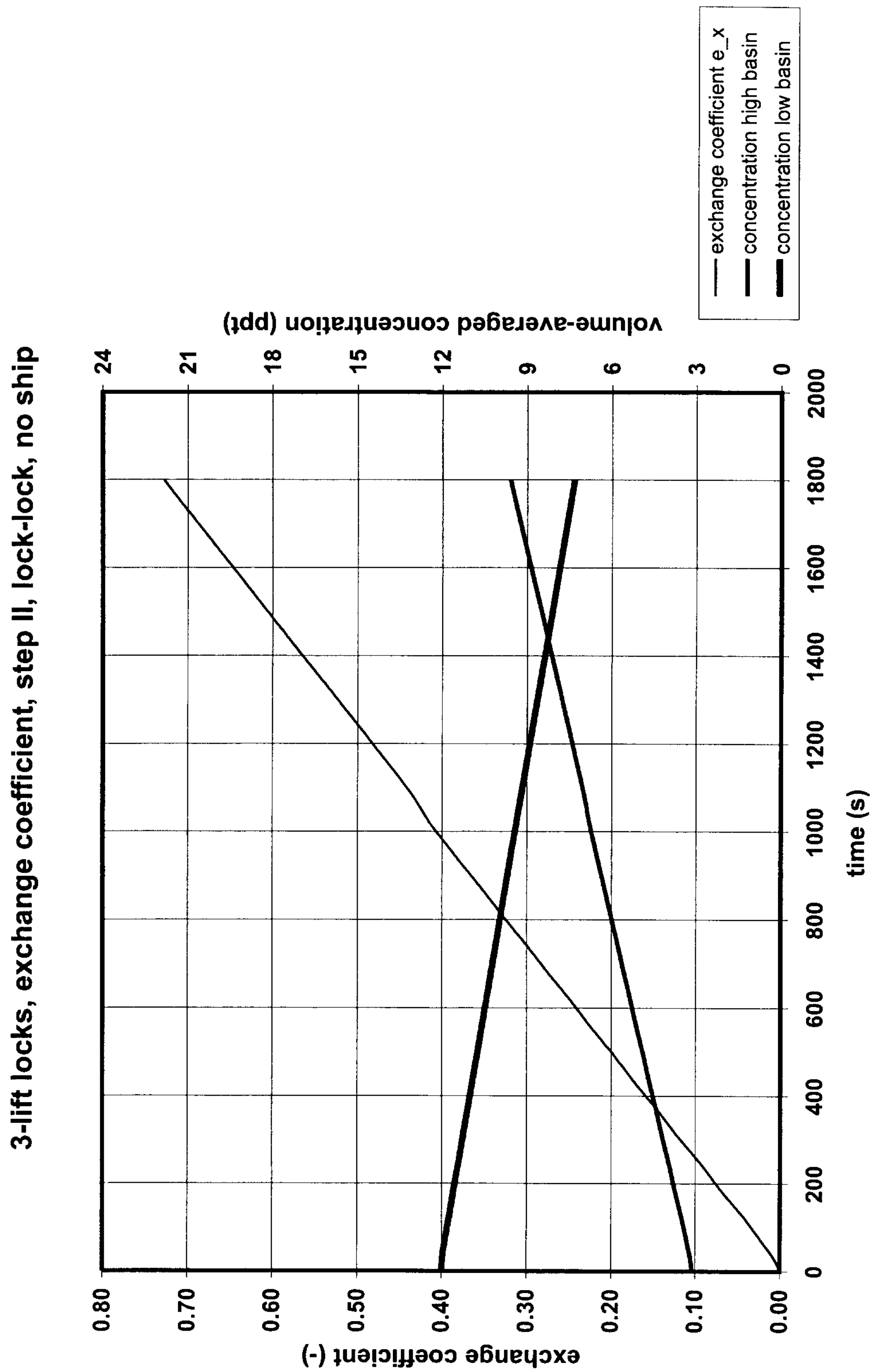
3-lift locks	

WL | DELFT HYDRAULICS

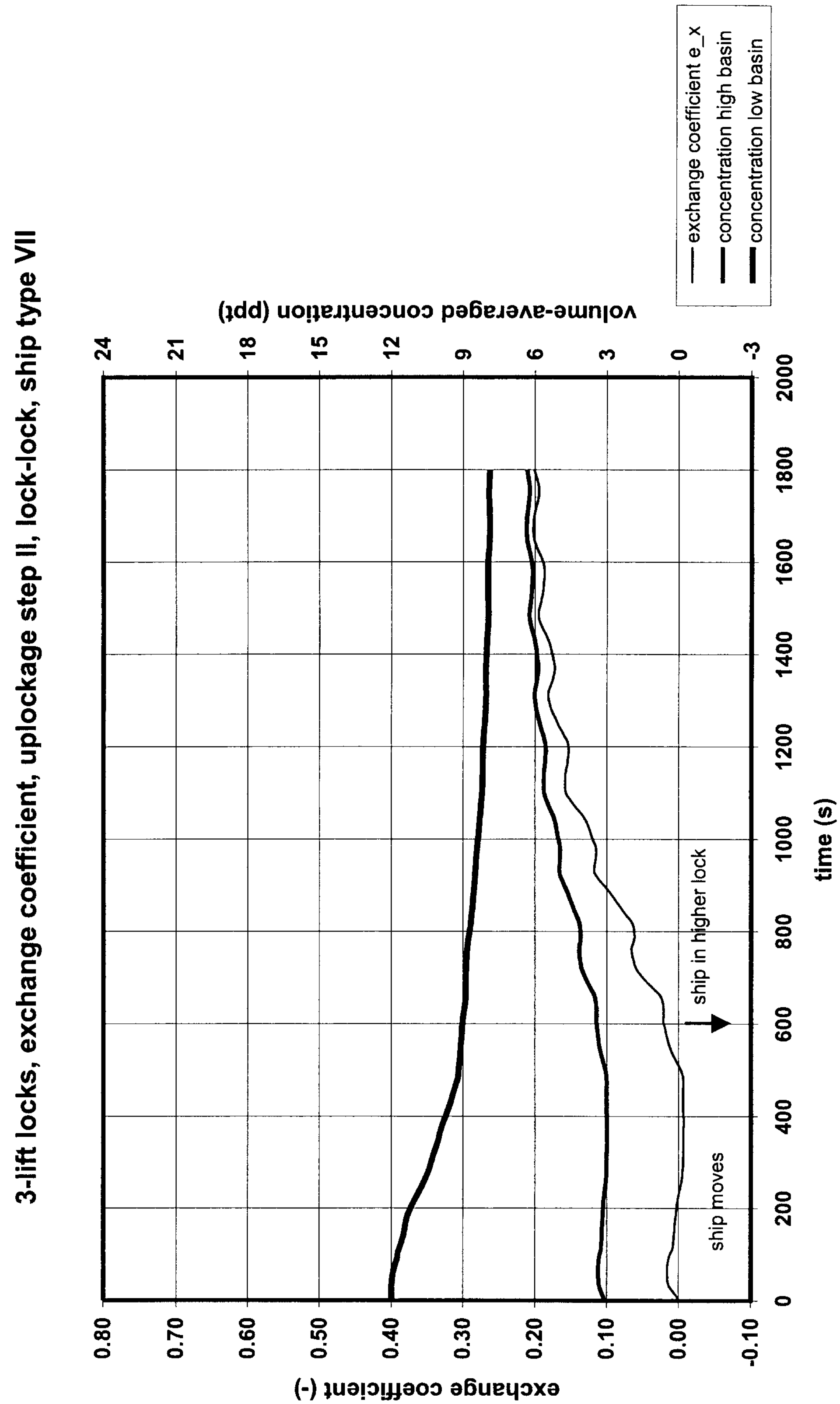
Q 3039	Fig. 5.1



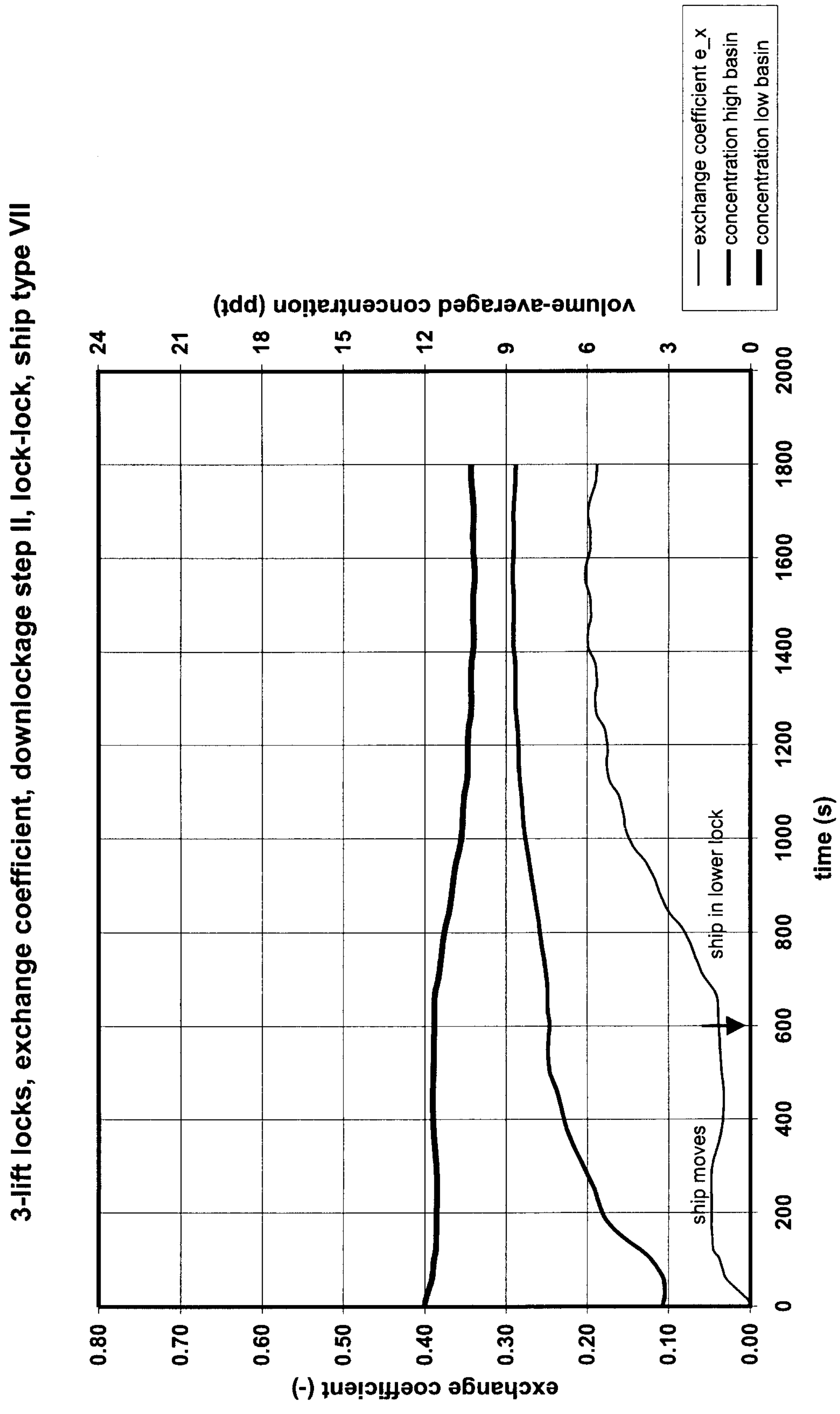
RESULTS OF DELFT3D COMPUTATION VOL-AVERAGED SALINITY OF LOCK, EMPTYING, NO SHIP	3-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.2



RESULTS OF DELFT3D COMPUTATION EXCHANGE COEFFICIENT, STEP II, NO SHIP		
	3-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.3



RESULTS OF DELFT3D COMPUTATION EXCHANGE COEFFICIENT, UPLOCKAGE STEP II, SHIP TYPE VII	3-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.4

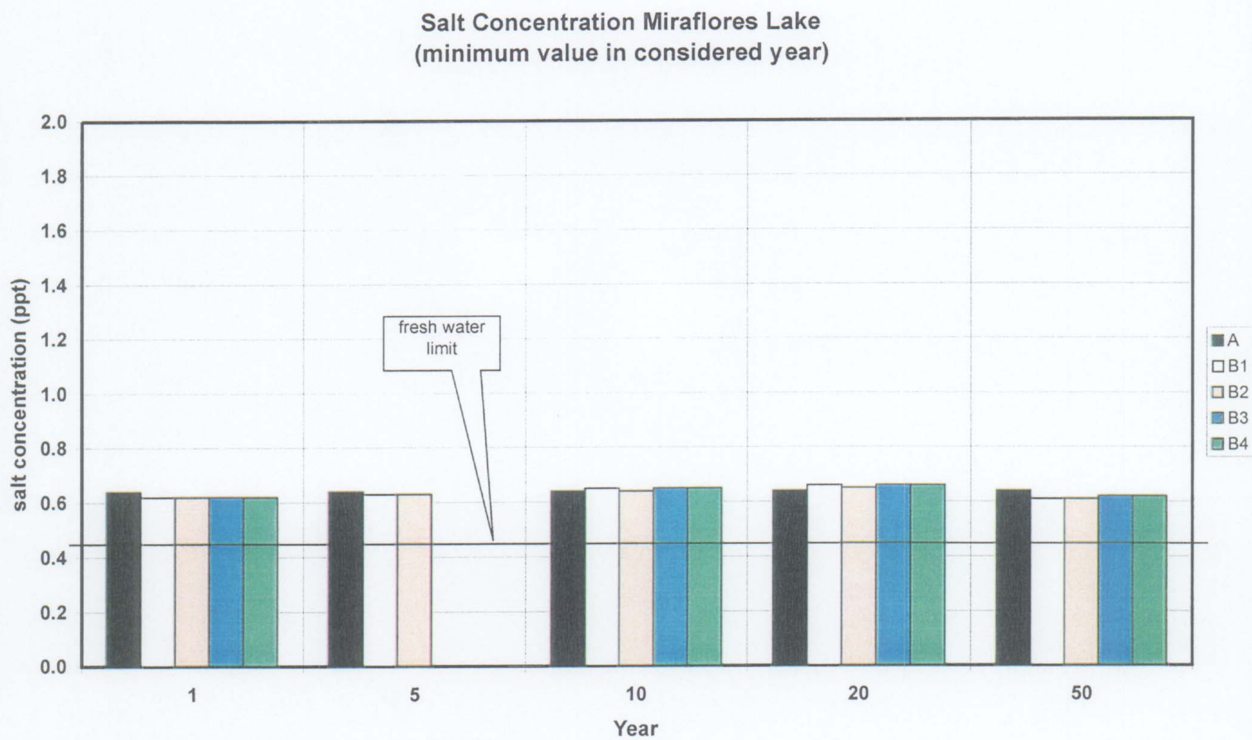


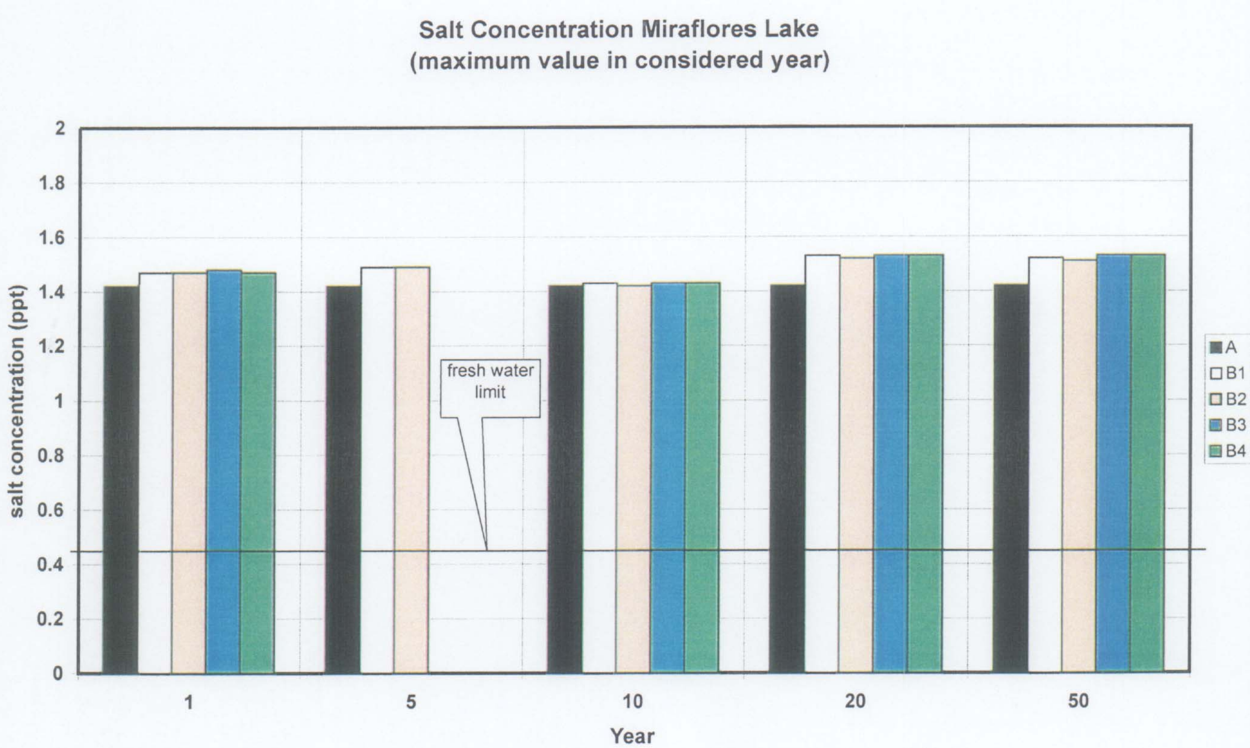
RESULTS OF DELFT3D COMPUTATION
EXCHANGE COEFF., DOWNLOCKAGE STEP II, SHIP TYPE VII

3-lift locks	

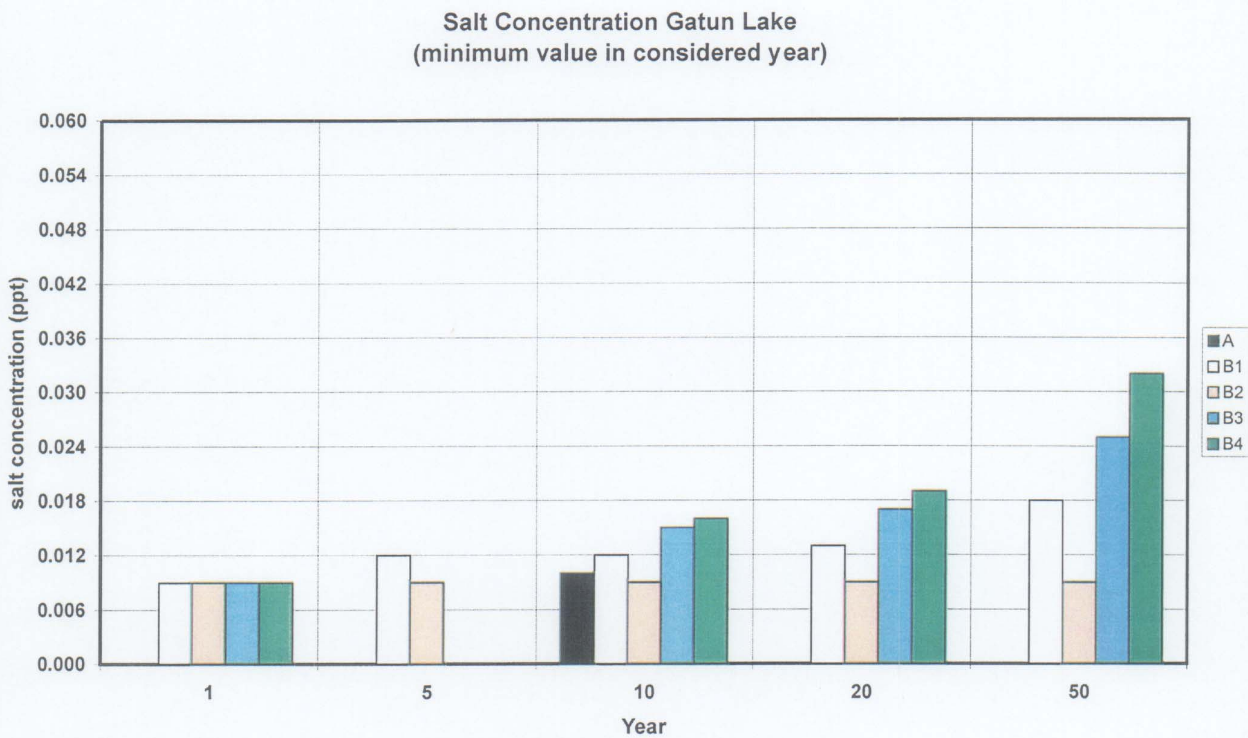
WL | DELFT HYDRAULICS

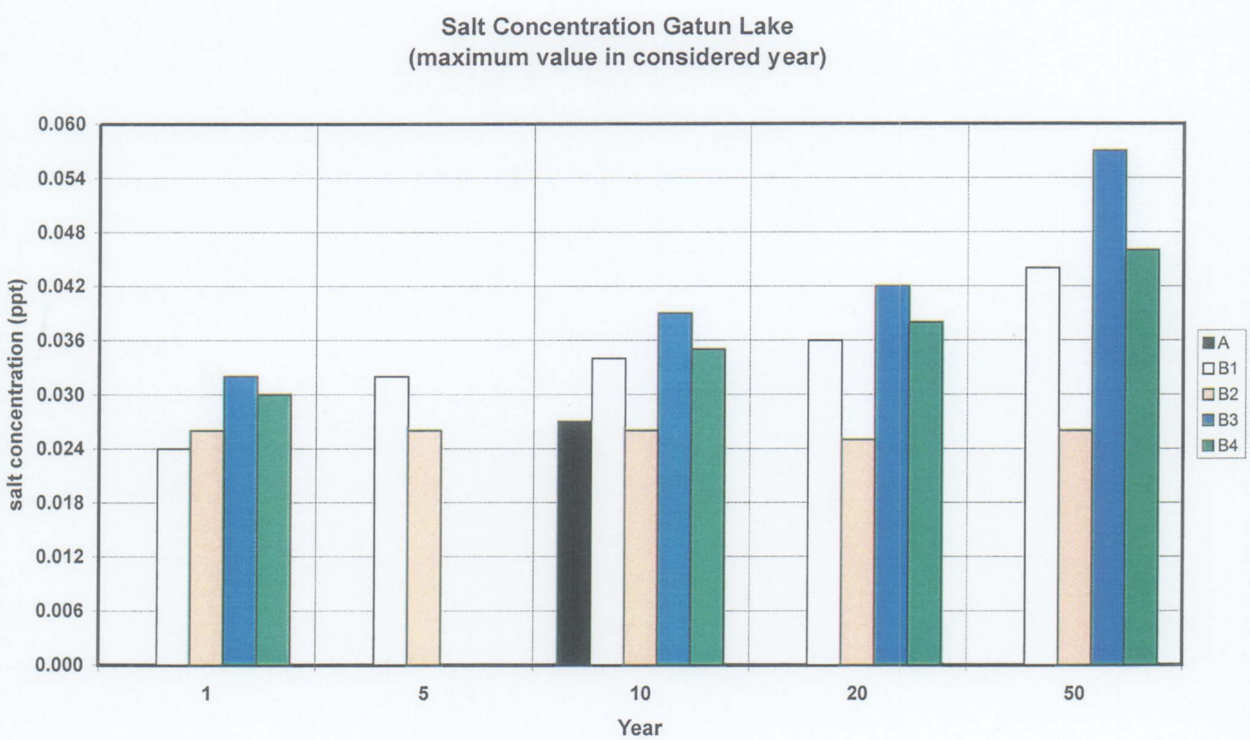
Q 3039 | Fig. 5.5



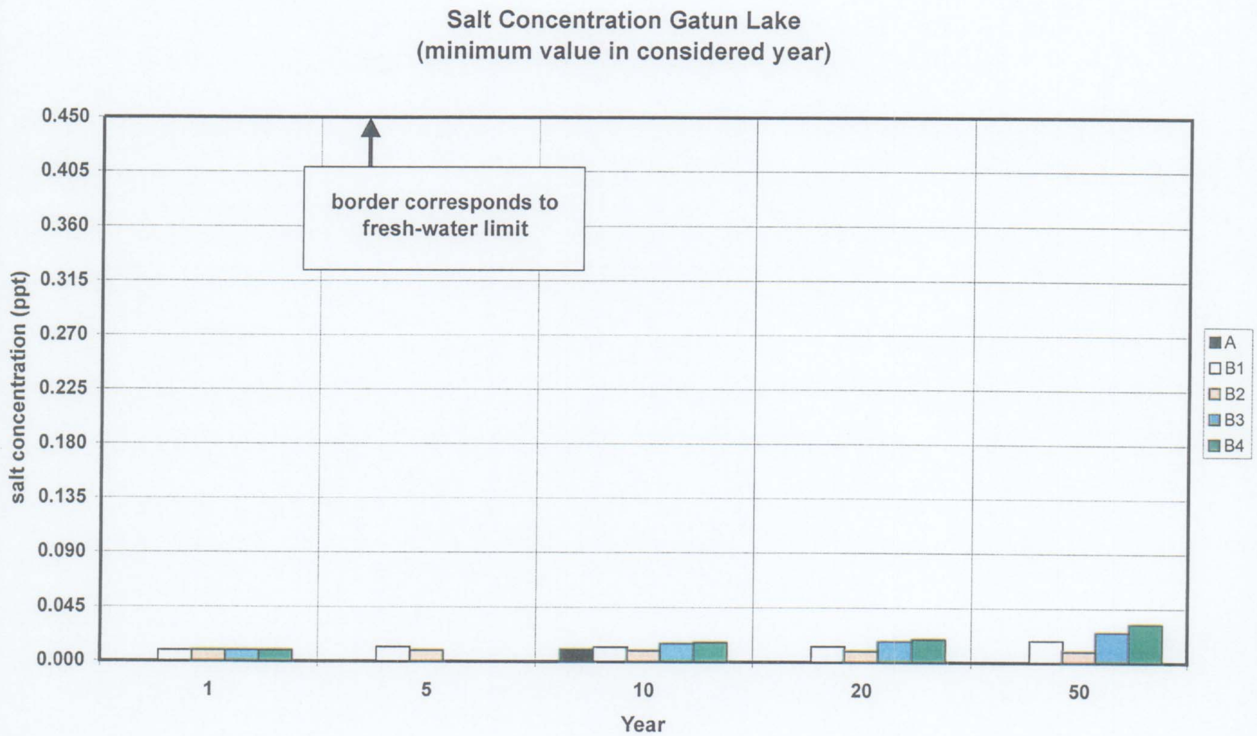


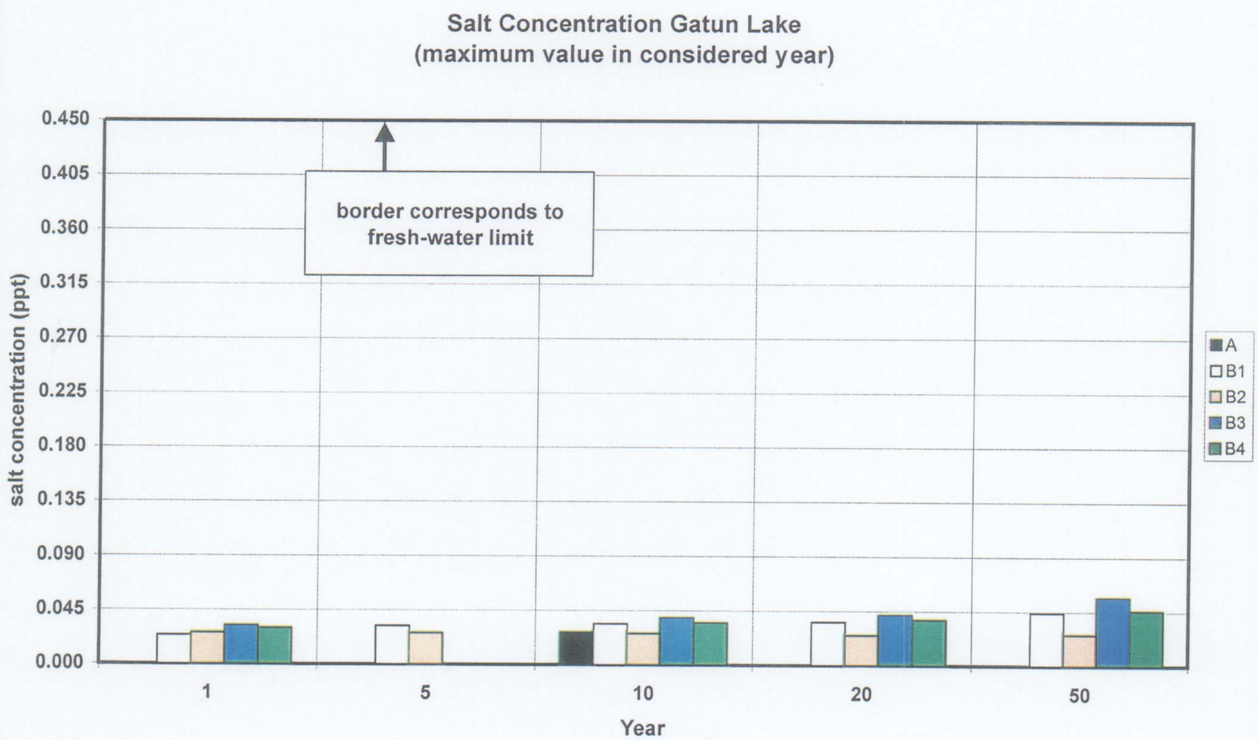
SALT CONCENTRATION MIRAFLORES LAKE maximum and minimum value in considered year	3-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 7.1





SALT CONCENTRATION GATUN LAKE maximum and minimum value in considered year		
	3-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 7.2





SALT CONCENTRATION GATUN LAKE maximum and minimum value in considered year in relation to fresh-water limit	3-lift locks
WL | DELFT HYDRAULICS	Q 3039 — Fig. 7.2a

Figures Simulations

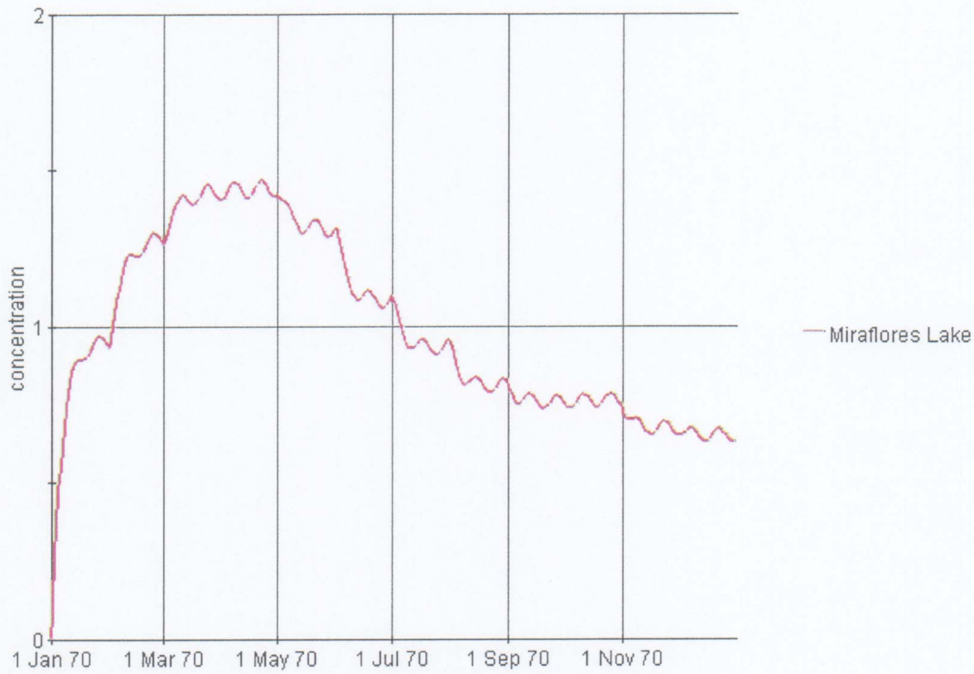


Figure A-1, 1 Existing Situation. Case validation. Salt concentration Miraflores Lake after 1 year (output interval: day)

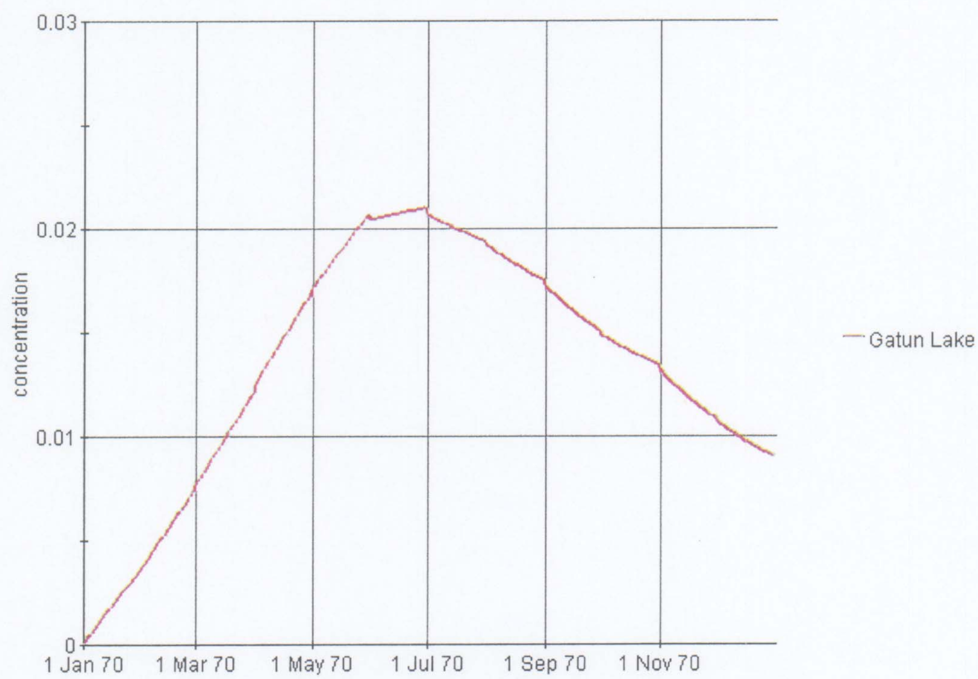


Figure A-1, 2 Existing situation. Case validation. Salt concentration Gatun Lake after 1 year (output interval: day)

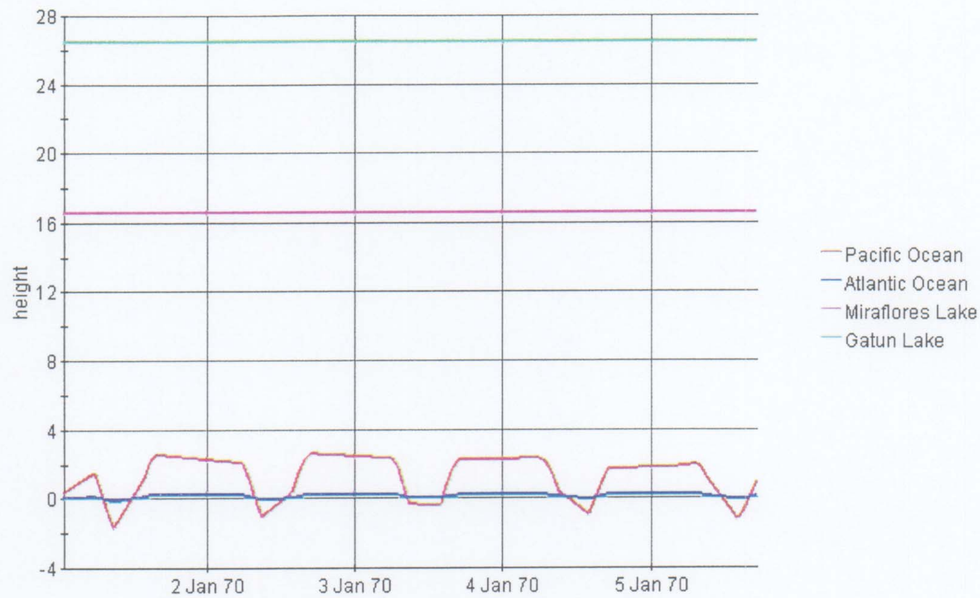


Figure TC8, 1 Test case 8. Water levels Pacific and Atlantic Ocean, Miraflores Lake and Gatun Lake (output interval: scenario)

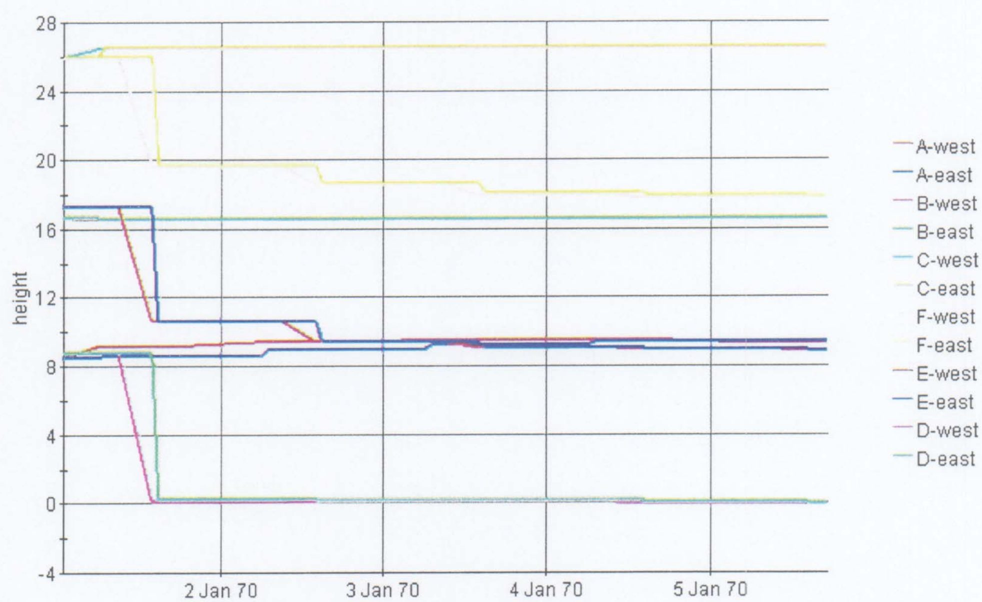


Figure TC8, 2 Test case 8. Water levels of locks A, B, C, D, E and F (output interval: scenario)

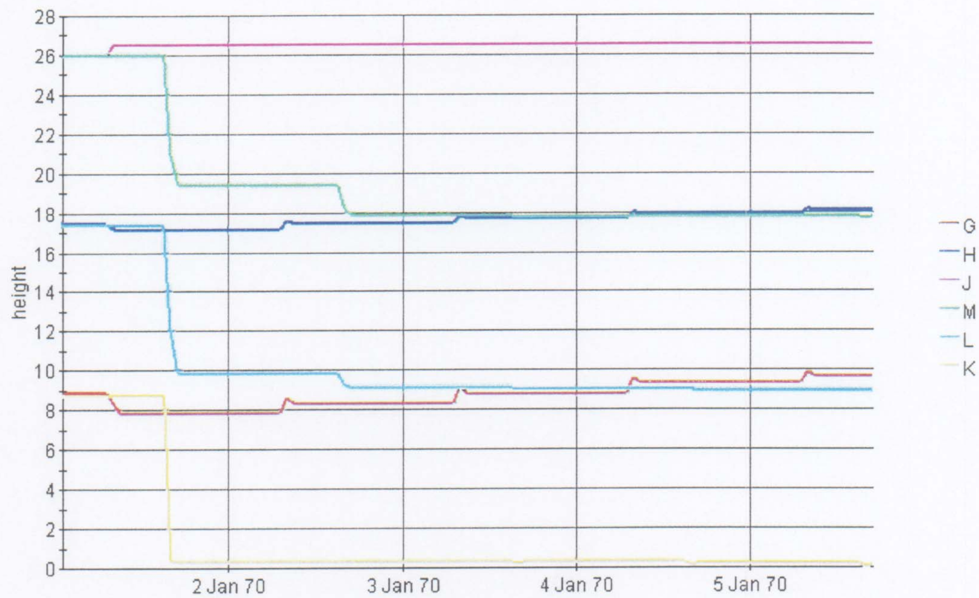


Figure TC8, 3 Test case 8. Water levels of locks G, H, J, M, L and K (output interval: scenario)

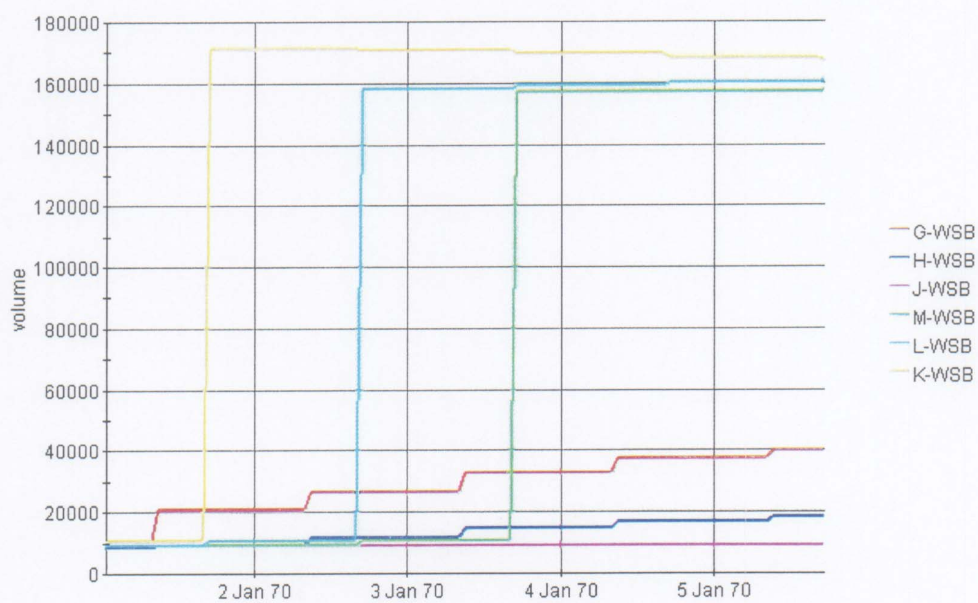


Figure TC8, 4 Test case 8. Water volumes of wsb's of locks G, H, J, M, L and K (output interval: scenario)

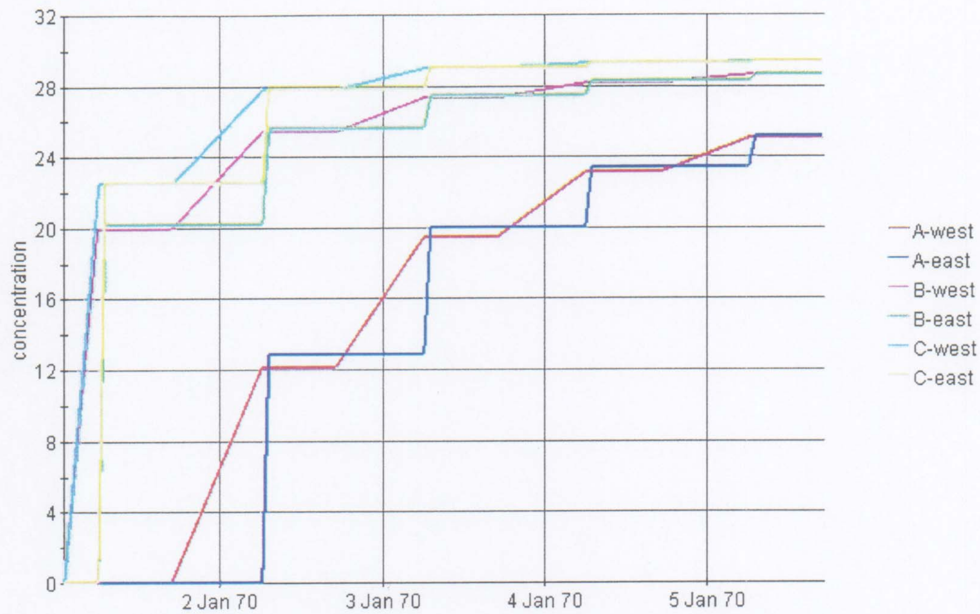


Figure TC8, 5 Test case 8. Salt concentration of locks A, B and C (output interval: scenario)

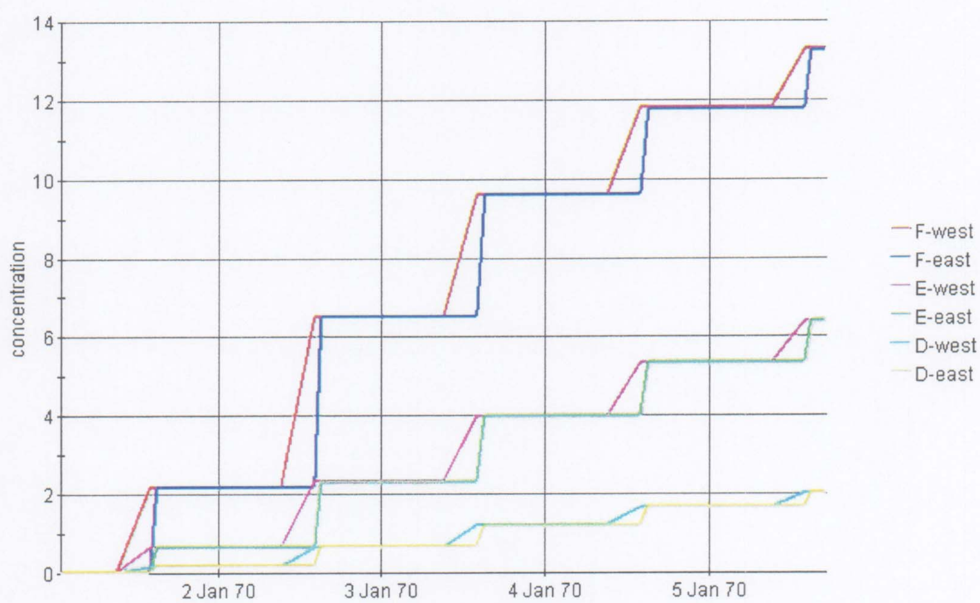


Figure TC8, 6 Test case 8. Salt concentration of locks D, E and F (output interval: scenario)

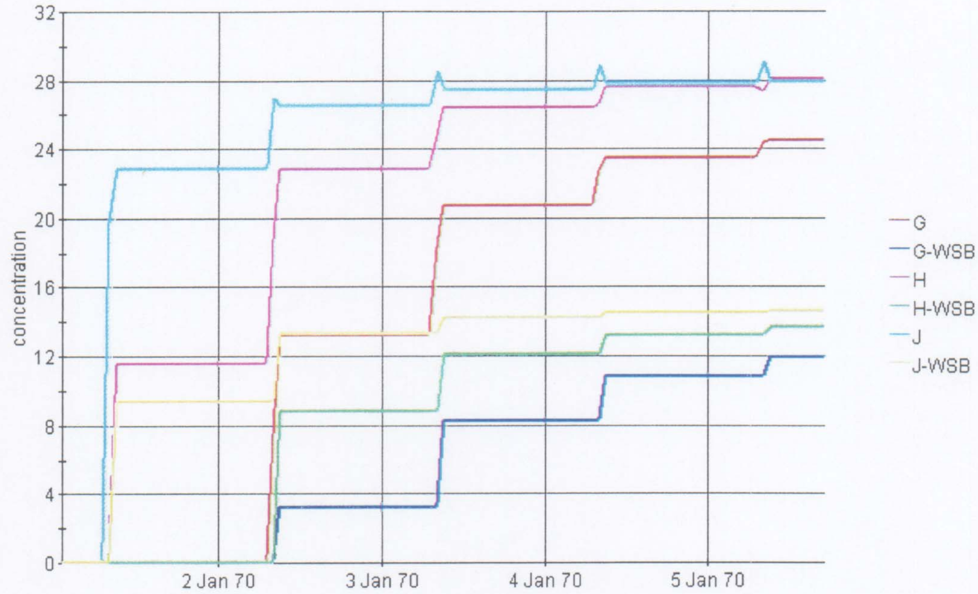


Figure TC8, 7 Test case 8. Salt concentration of locks G, H and J and wsb's (output interval: scenario)

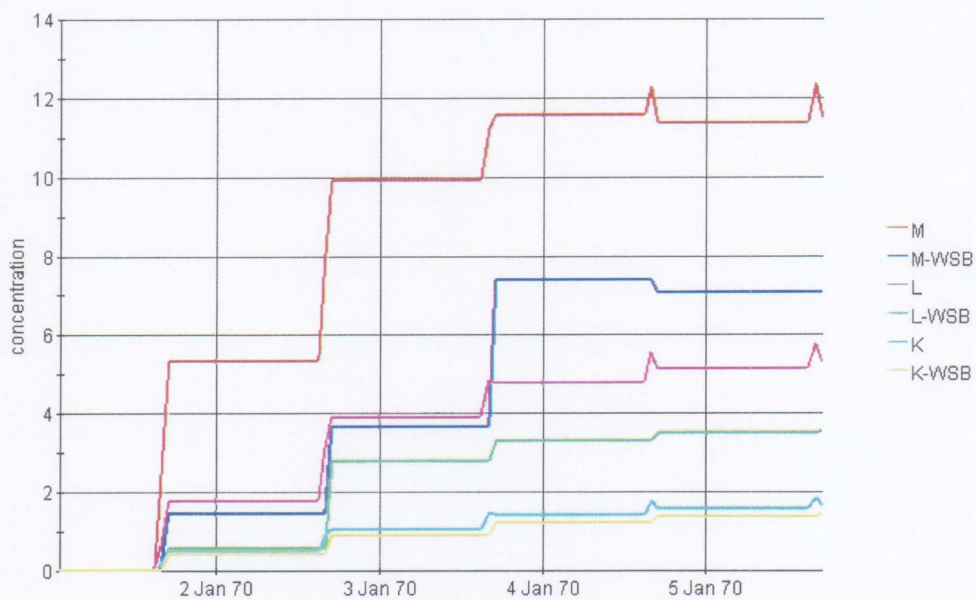


Figure TC8, 8 Test case 8. Salt concentration of locks M, L and K and wsb's (output interval: scenario)

Figure A-10, 1 Case A-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

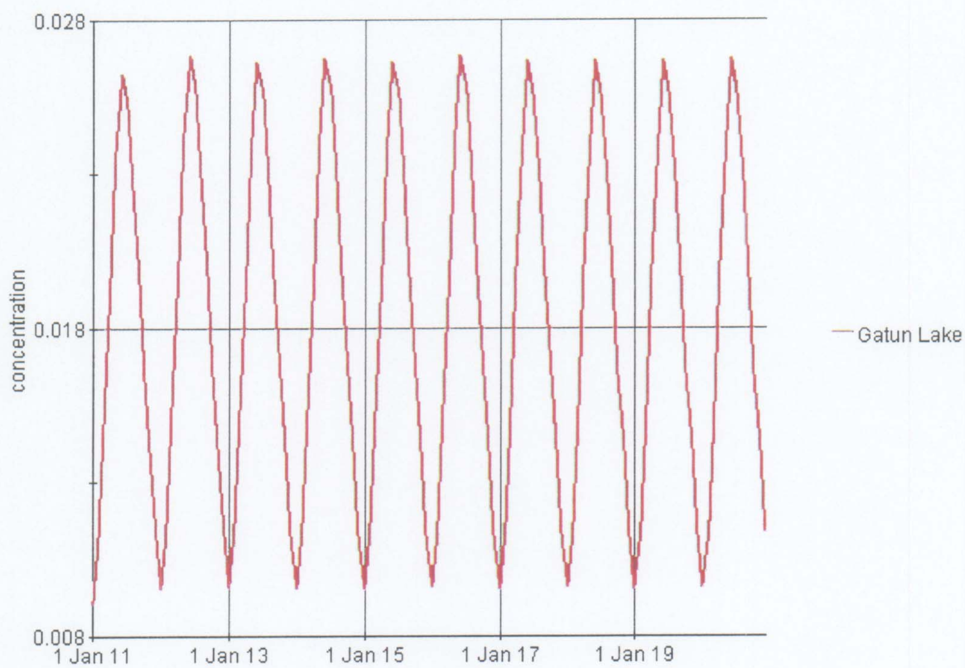


Figure A-10, 2 Case A-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

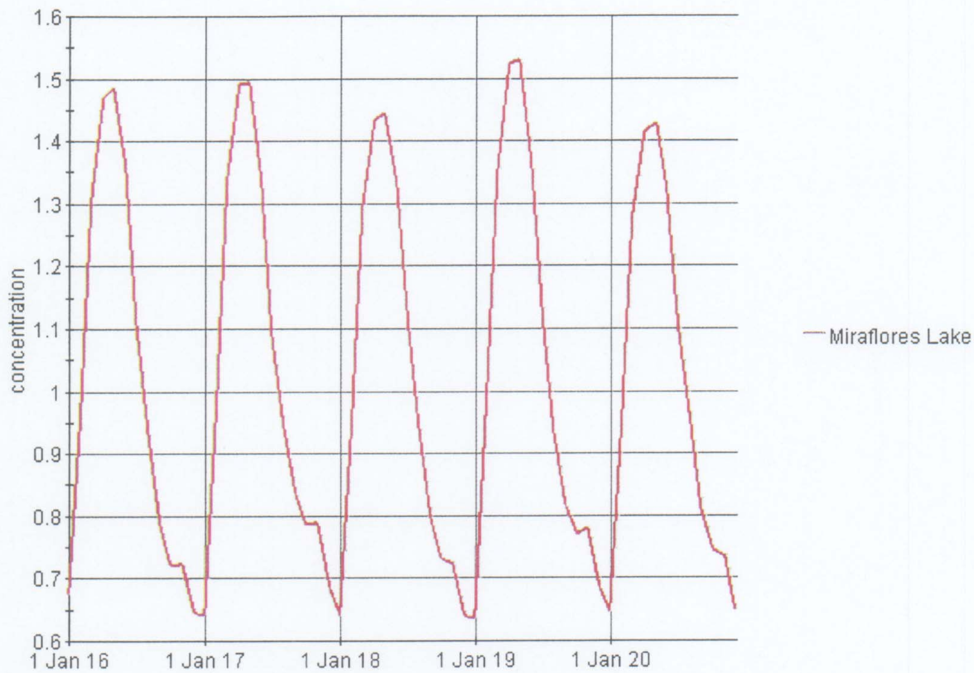


Figure B1-10, 1 Case B1-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

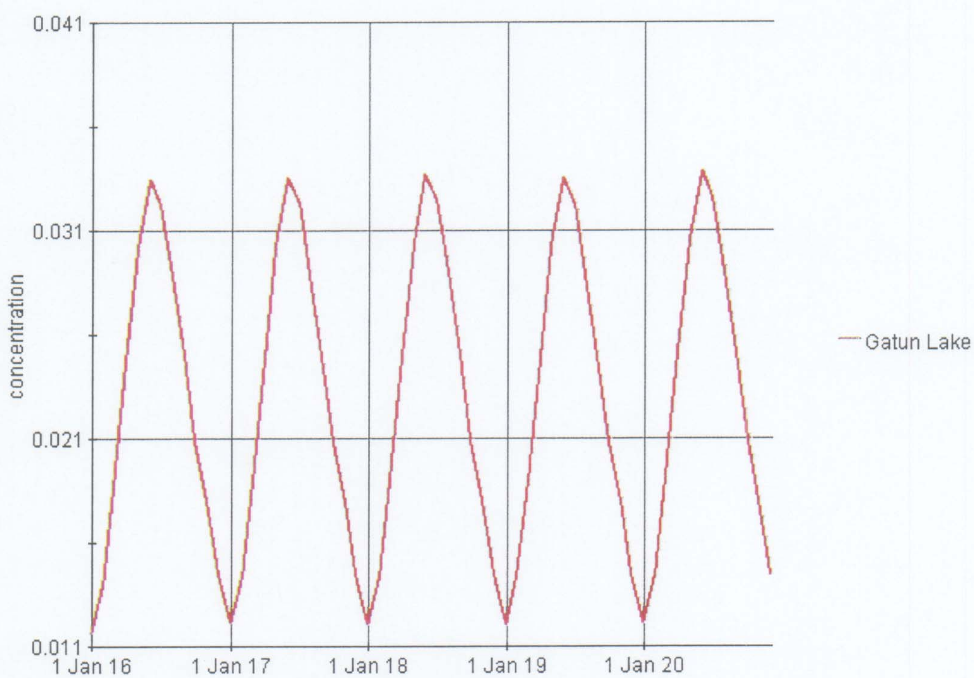


Figure B1-10, 2 Case B1-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

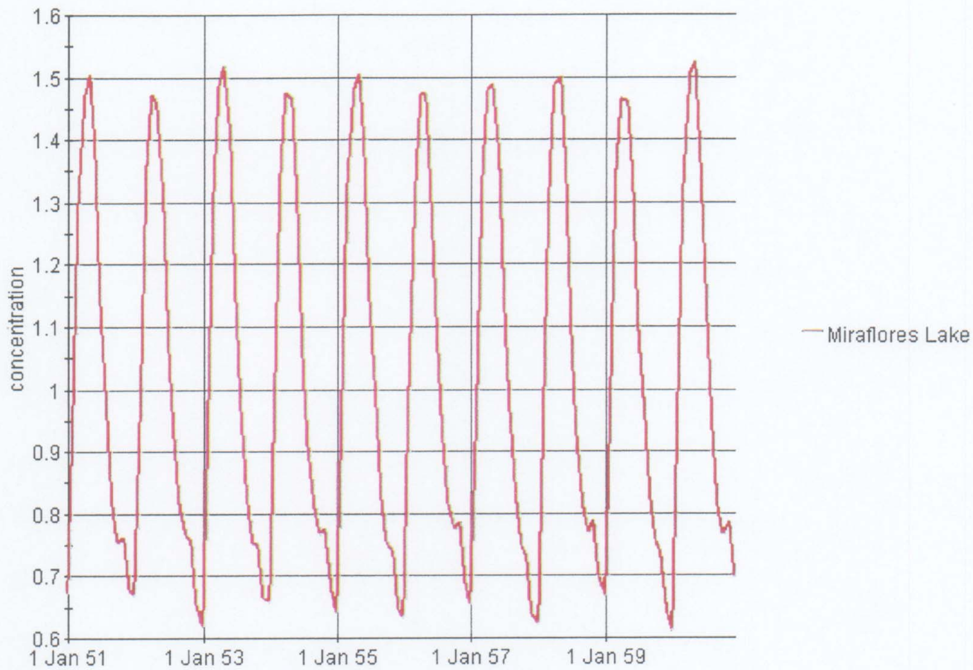


Figure B1-50, 1 Case B1-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

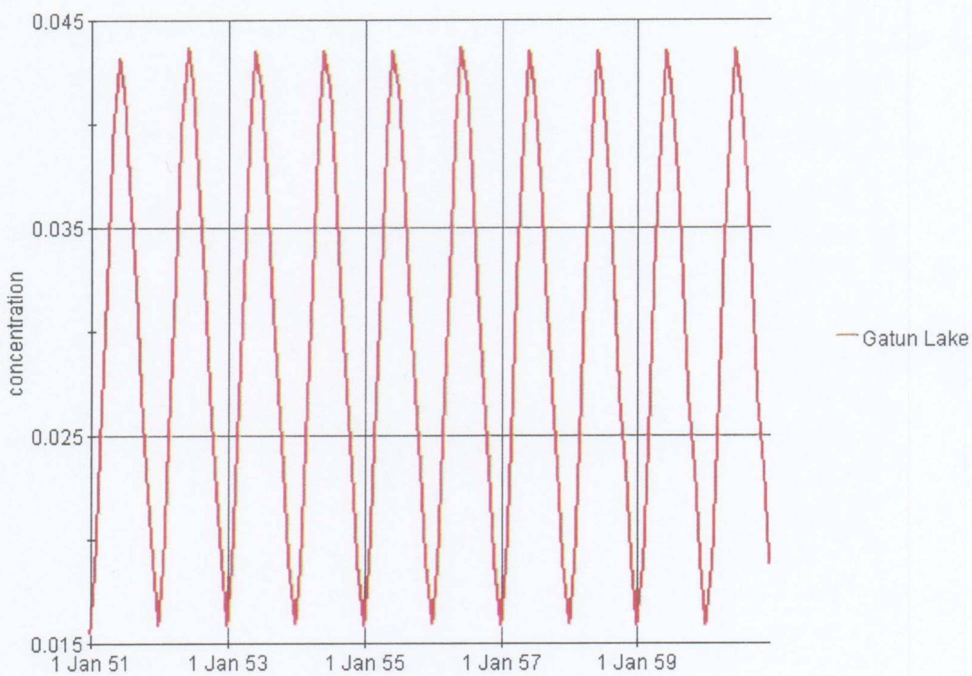


Figure B1-50, 2 Case B1-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

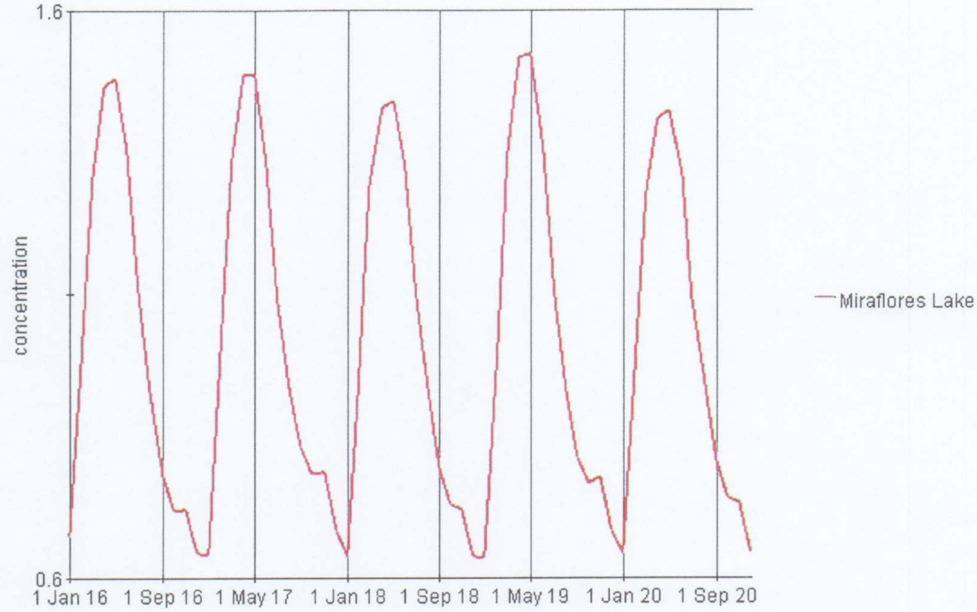


Figure B2-10, 1 Case B2-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

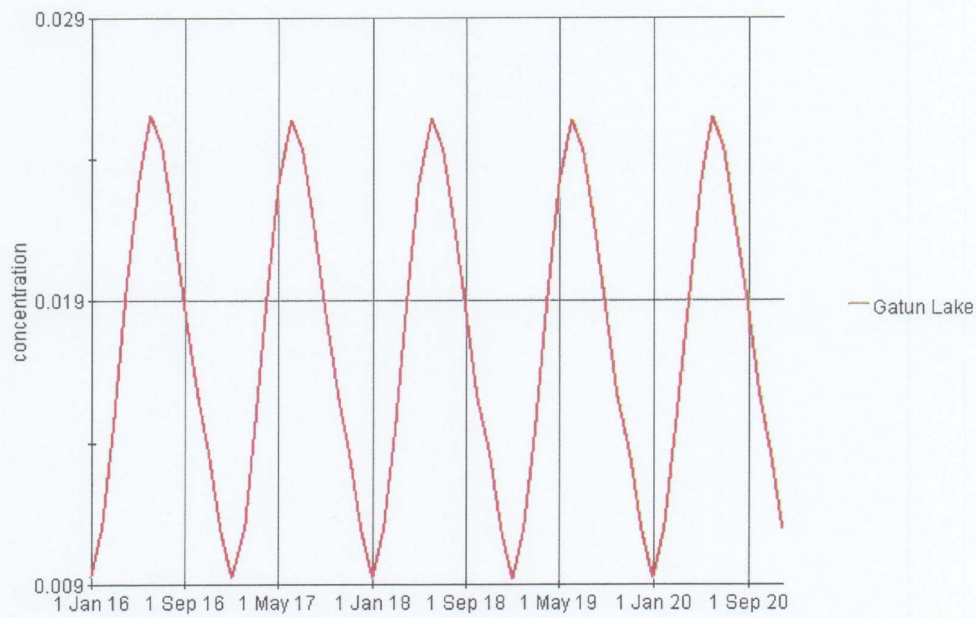


Figure B2-10, 2 Case B2-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

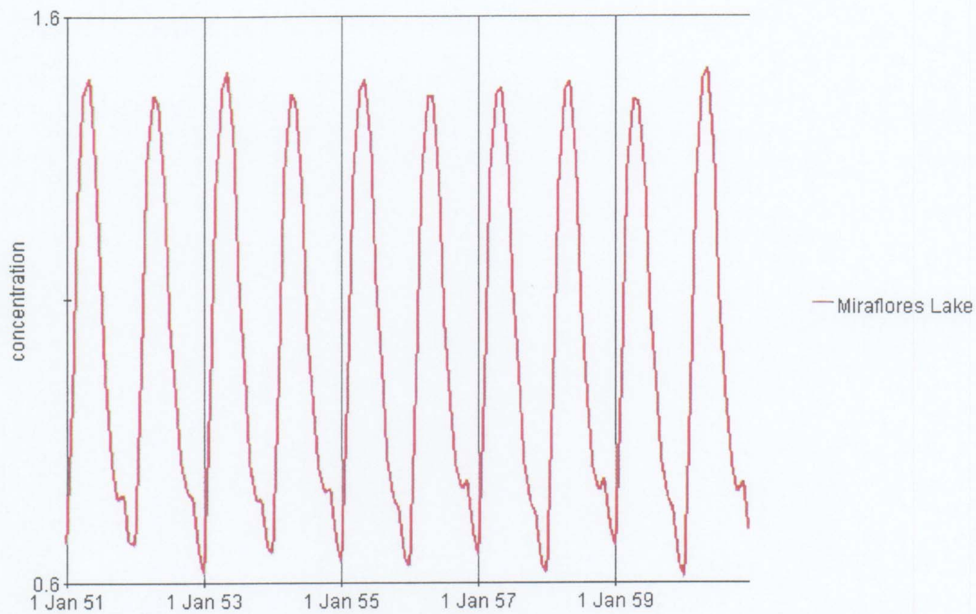


Figure B2-50, 1 Case B2-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

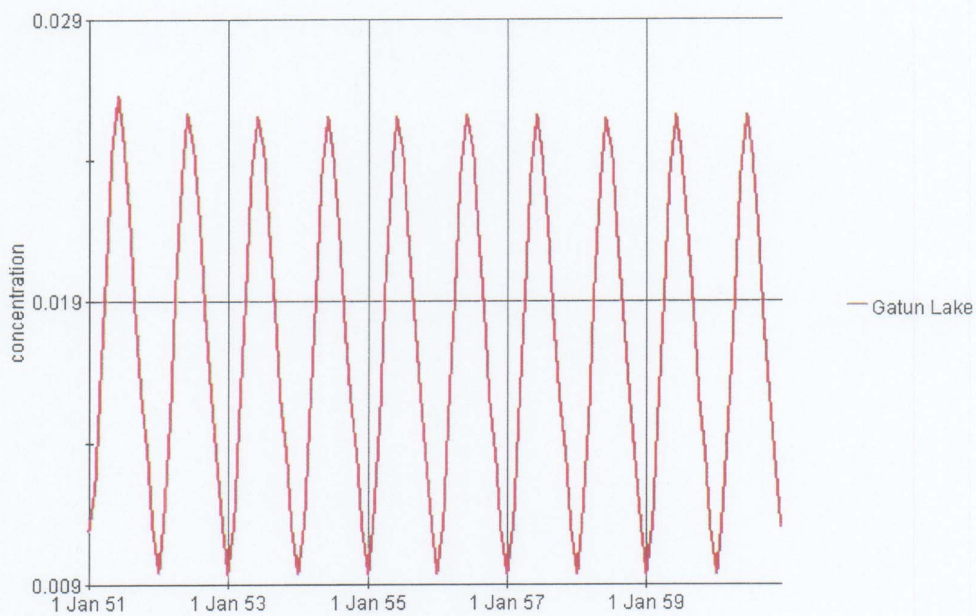


Figure B2-50, 2 Case B2-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

Figure B3-10, 1 Case B3-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

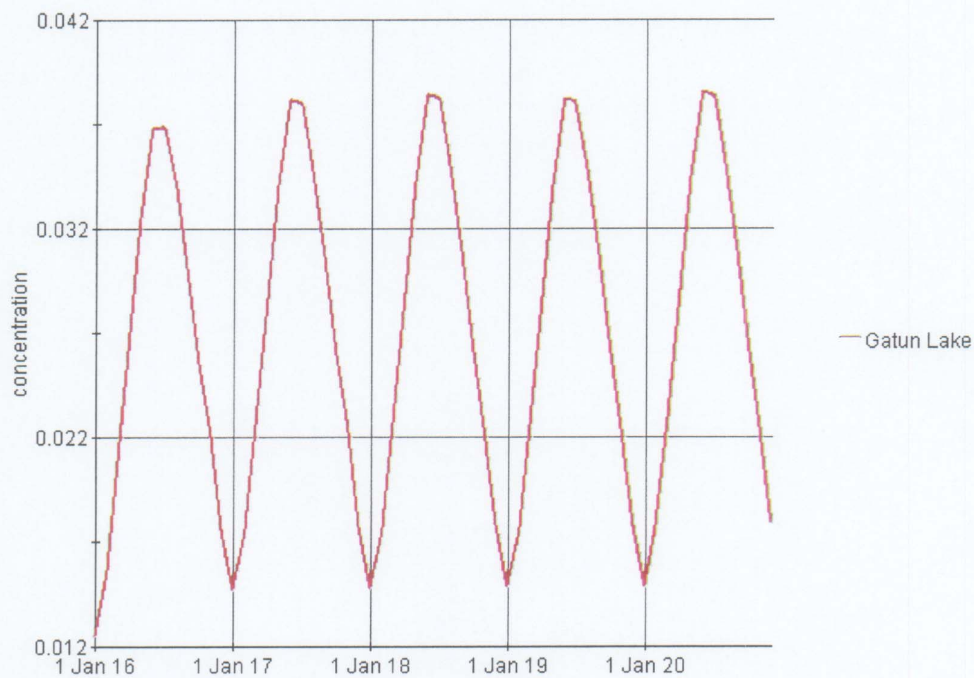


Figure B3-10, 2 Case B3-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

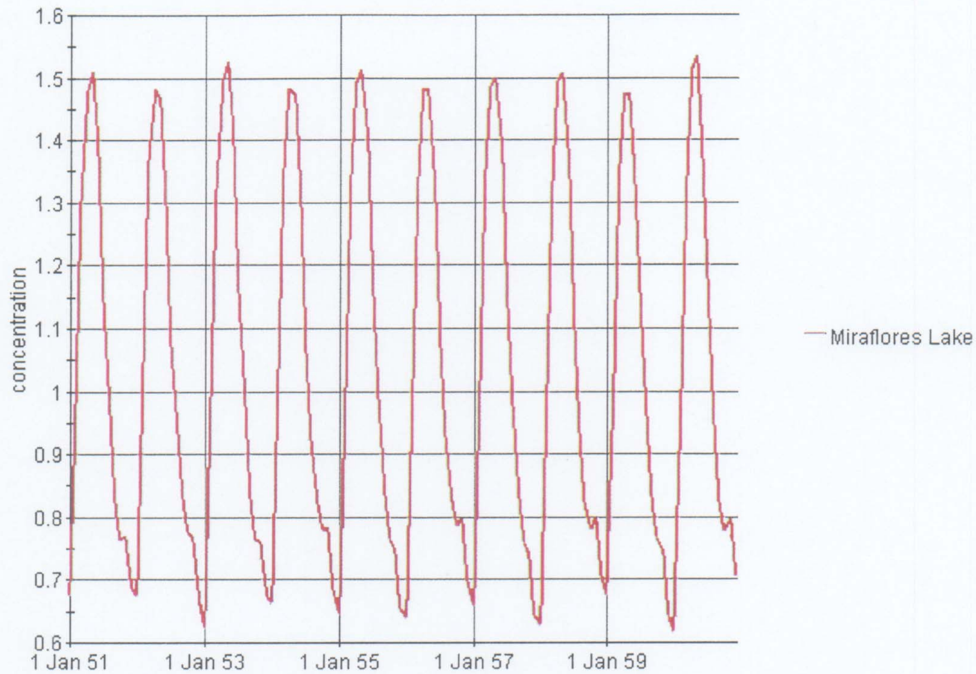


Figure B3-50, 1 Case B3-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

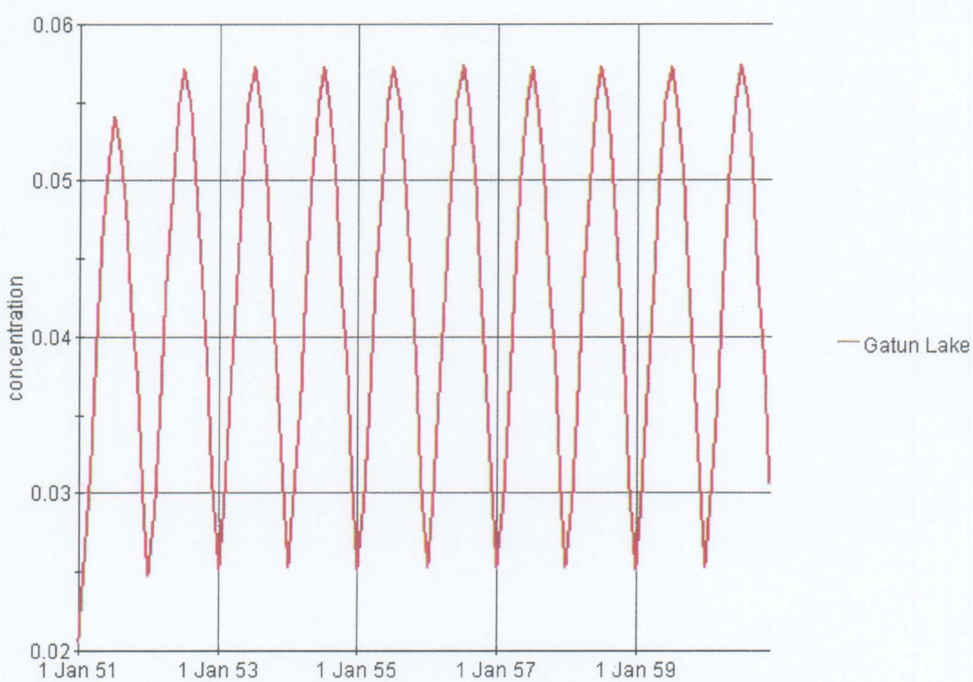


Figure B3-50, 2 Case B3-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

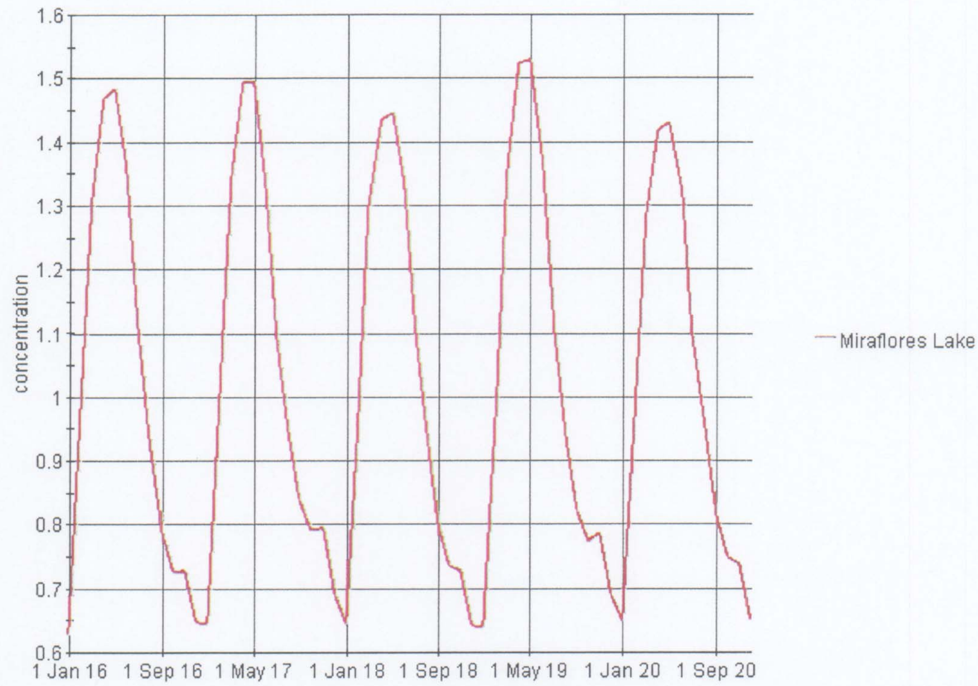


Figure B4-10, 1 Case B4-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

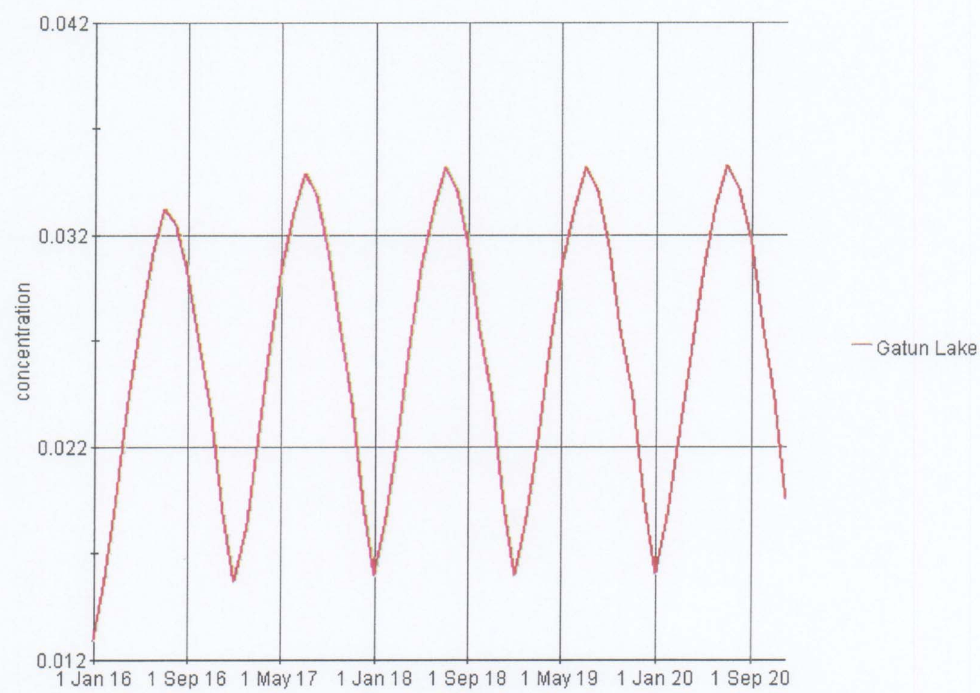


Figure B4-10, 2 Case B4-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

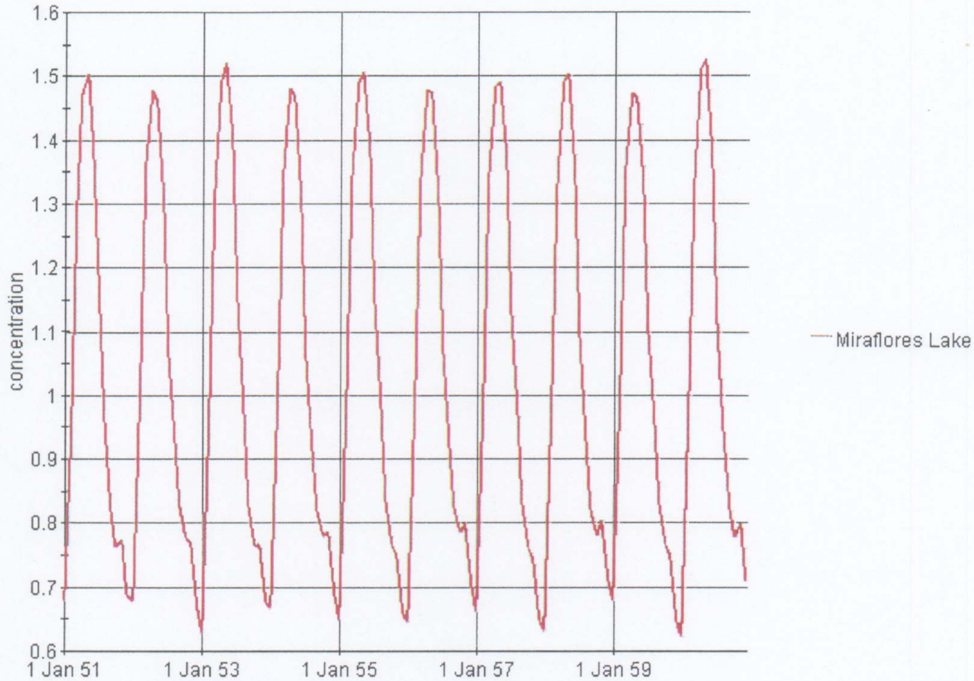


Figure B4-50, 1 Case B4-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

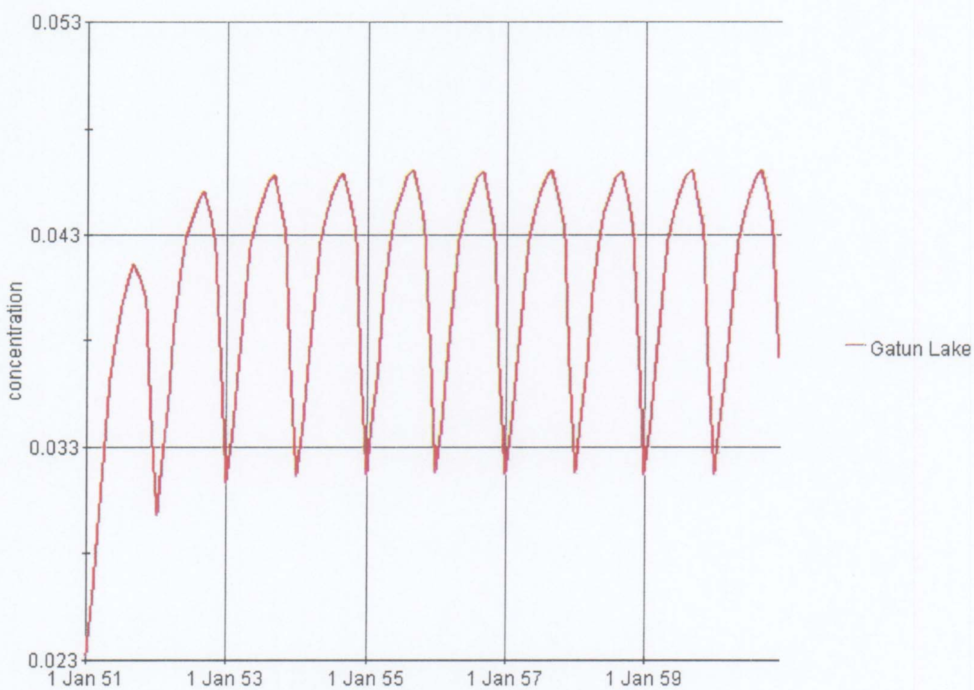


Figure B4-50, 2 Case B4-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

Report D
Two-lift Post-Panamax Locks

Contents Report D

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1 Introduction

The present Report deals with the salt water intrusion of the *two-lift lock* configuration of Post-Panamax Locks on the future, third shipping lane. The salt water intrusion is additional to the salt water intrusion through the existing locks. The new two-lift locks may be provided with water saving basins.

The following items will be adressed in the present report:

- review of concept design of US Army Corps of Engineers (USACE) for the *two-lift lock* configuration of Post-Panamax Locks;
- extension of the salt-water intrusion simulation model built for the existing situation with a new shipping lane; this new lane is provided with *two-lift locks* and water saving basins at either side of the canal (the use of water saving basins is optional in the simulation model);
- selection of salt exchange coefficients that will be used in the simulation;
- simulation of salt water intrusion for the *two-lift lock* configuration of Post-Panamax Locks and analysis of results.

2 Concept design of USACE for two-lift lock configuration

2.1 Data provided by ACP

The next reports and drawings have been provided by ACP:

Report

US Army Corps of Engineers (USACE)
'Panama Canal Concept Design of New Third Lane, Double-lift Design'
Main Report (Executive Summary pp 1-8; Section 5.5.3 Recommended Plan pp39-44; Appendix A Design Water Elevations pp 7-10; Appendix E Hydraulic Analysis and Designs pp 1-80 and plates E-1 – E-18), 4 April 2003.

Drawings of USACE

Drawing number	Date	Title
ACP-R-20/2	Mar 2003	Alternative 1, bottom interlaced laterals, plan and elevation
ACP-R-20/3	Mar 2003	Alternative 1, filling system 1, lock chamber and water saving basins, plan and elevation
ACP-R-20/10	Mar 2003	Miter gate monoliths, sections A & B
ACP-R-20/11	Mar 2003	Miter gate monoliths, section C
ACP-R-20/12	Mar 2003	Lock and water saving basins, sections
ACP-R-20/13	Mar 2003	Water saving basins, sections
ACP-R-20/14	Mar 2003	Lock and water saving basins, sections

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 lock system at Atlantic side

The two-lift lock configuration of Post Panamax Locks designed by USACE, connects the canal entrance at the Atlantic side with Gatun Lake. The new locks are situated east of Gatun Locks. Each of two locks is provided with two water saving basins, arranged side by side at the west side of the locks.

The next data was taken by USACE as starting points for their design *(all levels refer to PLD)*:

Hydraulic conditions

Gatun Lake: mean water level +25.91 m, maximum water level +26.67 m, minimum water level +23.93 m.
Canal entrance at the Atlantic side: mean sea level +0.06 m, extreme high tide +0.56 m, extreme low tide –0.38 m.

Lock chambers

Minimum utilizable length of lock chambers between inner gates 426.7 m, width 60.96 m, minimum water depth above sills 18.29 m, minimum hydraulic freeboard 1.31 m. Locks can be operated with or without the two water saving basins of each lock; in the latter case lock-to-lock water transfer is practised. The water saving rate for each individual lock chamber is minimum 50% (when water saving basins are in use). The target filling or emptying time is 12-15 minutes when water saving basins are not in use.

Post-Panamax ships

Dimensions of design ships: container ships 125,000 dwt (water displacement 209,000 ton) and bulk carriers 135,000 dwt (water displacement 169,000 ton).

Two-lift lock design

The USACE-design for the two-lift lock configuration at the Atlantic side of the canal is schematically shown in Figure 2.2. The new locks have a width of approximately 61 m. Each lock chamber is provided with a double set of miter gates at both ends. Sills are designed to support the gates; they protude about 0.6 m above the floor of the lock chambers; the chamber floors themselves are fully flat. The nominal length of the lock chambers between the center line of the upper gates and the center line of the lower gates is about 515 m.
When going upwards from the Atlantic tailbay to Gatun Lake the steps in sill level are successively 12.15 m and 12.16 m. Sill level –18.67 m of the lower lock is designed starting from the minimum required water depth of 18.29 m and a mean low-tide water level in the tailbay of –0.38 m. Sill level +5.64 m of the forebay in Gatun Lake follows from the minimum lake level +23.93 m and the minimum required water depth of 18.29 m. Floor levels are about 0.6 m lower.

Two water saving basins are arranged side by side along each of the lock chambers (see Figures 2.2 and 3.4). The length and width of the water saving basins differ from the horizontal dimensions of the lock chambers, but the capacity of the water saving basins is such, that at least 1/4 of the water exchange volume can be saved in each basin. The two water saving basins of a lock have different bottom levels; in addition, the bottom level near the water inlet is designed 2 m lower than the bottom level near the sides of a basin.

The filling and emptying system consists of a multiport system. The main water culverts at both sides of the locks run along the full length of the locks from the intakes in the forebay to the outlets in the tailbay. These culverts are provided with valves to facilitate a controled flow of water from forebay to upper lock, from lock to lock, and from lower lock to tailbay. Lateral culverts, which spring alternately from the main culverts in left and right lock wall, are designed in the floor of the lock chambers at a center to center distance of about 2 m

along the full chamber length. Each bottom lateral has six openings in the lock chamber floor.
Each water saving basin (wsb) is connected to the main, longitudinal culverts by means of two gated transverse culverts. Filling of a lock chamber starts with emptying of the lower wsb and than the upper wsb (see Figure 3.4). The remaining water portion is supplied from the adjacent higher lock or forebay. Emptying of a lock chamber occurs in a reverse sequence: first the upper wsb is filled, than the lower wsb. The remaining water portion is discharged to the adjacent lower lock chamber or tailbay. Filling or emptying of a wsb stops when an equal water level is obtained in wsb and lock chamber. The same holds for the transfer of water from forebay to lock chamber etc.

2.3 Lock system at Pacific side

Though the two-lift lock system has been designed by USACE for the Atlantic side of the canal, we will assume, for the extension of the salt-intrusion simulation model, that a similar lock system will be constructed at the Pacific side. However, we will adapt the floor levels of the locks because of the much greater tidal variation at the Pacific side of the canal (mean water level in the Pacific entrance of the canal +0.30 m, extreme high tide +3.60 m, extreme low tide –3.44 m, mean low tide –2.32 m).
In the existing situation the difference between floor level of the lower locks at the Pacific side and the lower locks at the Atlantic side is about 2.0 m. When we start from mean low tide at the Pacific side of –2.32 m and a minimum required water depth of 18.29 m, a sill level of –20.62 m and a floor level of –21.22 m is found for the lower lock of the two-lift lock system. The sill level of the forebay can be the same as at the Pacific side, namely +5.64 m. The steps in sill level when going up from the Atlantic tailbay to the forebay in Gatun Lake are selected as 13.13 m and 13.13 m successively. All other lock dimensions and the layout of water saving basins are similar as at the Pacific side, but the floor levels of water saving basins are adapted to the selected floor levels and water levels of the corresponding lock chambers. The adopted two-lift lock system at the Pacific side is shown schematically in Figure 2.1.

2.4 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 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 2.1 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 has been set up for the existing situation (see description in Report A, dated June 2003) and is extended and adapted to the situation with a new shipping lane and two-lift locks. A scheme of the extended model is shown in Figure 3.1. 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 (see Figures 3.5 and 3.6). 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, wsb's, forebays and tailbays of locks, lakes and entrances) are regarded as nodes in the numerical simulation model. The nodes and the hydraulic connections between the nodes are shown in the scheme of Figure 3.1. In the present study we name the locks as indicated in Figure 3.1: locks in the existing lanes at the Pacific side: A-west and A-east, B-west and B-east, C-west and C-east; locks in the existing lanes at the Atlantic side: D-west and D-east, E-west and E-east, F-west and F-east, locks in the new lane at the Pacific side: P and Q; locks in the new lane at the Atlantic side: R and S.

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.

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 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 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. A special scenario is the scenario that describes a 'turn around' (change from northbound ship transits to southbound ship transits or reverse), and a water-release scenario that describes the water spills and water use for hydropower generation and cooling.

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, for example for each day of the week. Subsequently, day patterns are combined in a case (see scheme of Figure 3.2). A case contains information on start date and stop date of the simulation. Day patterns are handled one by one in the sequence of input. After the last day pattern has been handled the simulation model starts again with the first day pattern; this cyclical process continues until the end of the simulation. The user shall prepare a set of salt exchange coefficients (see Chapter 4) 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 3.10). 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 3.3.

3.2 Two-lift locks and wsb's in simulation model

In addition to the two existing shipping lanes a new lane with two-lift locks at both sides is defined in the simulation model. Each lock is provided with water saving basins (wsb's). Because the two wsb's of a lock are filled or emptied one after another and the sequence of filling and emptying is always the same, the set of two wsb's can for the purpose of salt-water intrusion simulation be replaced by a single wsb (see Figure 3.4). The storage capacity of this single wsb is equal to the capacity of the set of two wsb's; also the fill and emptying time is equal to the fill and emptying time of the set of two wsb's. The exchange coefficient in the salt balance is such selected that it is representative for the salt exchange between lock chamber and both individual water saving basins (see Chapter 5). The locks in the new lane can be operated with or without wsb's in the simulation model.

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} ($= l_{lock} \cdot b_{lock}$)
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)

3.4 Ship movements and turn arounds; vessel classes

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 (see hereafter) between an uplockage and a downlockage scenario.

With the new lane included a total number of 16 different ship movements and turn arounds can be distinguished. The 2-lift locks in the new lane can be operated with or without water saving basins. Table 3.1 gives an overview of the various ship movements in the simulation model.

no	*ship movement*	*lane*	*up- or downlockage*	*remarks*
1	Pacific Ocean to Gatun Lake	west lane	Uplockage	
2	Gatun Lake to Pacific Ocean	west lane	Downlockage	
3	Pacific Ocean to Gatun Lake	east lane	Uplockage	
4	Gatun Lake to Pacific Ocean	east lane	Downlockage	
5	Pacific Ocean to Gatun Lake	new lane	Uplockage	wsb's out of use
6	Gatun Lake to Pacific Ocean	new lane	Downlockage	wsb's out of use
7	Pacific Ocean to Gatun Lake	new lane	Uplockage	wsb's in use
8	Gatun Lake to Pacific Ocean	new lane	Downlockage	wsb's in use
9	Atlantic Ocean to Gatun Lake	west lane	Uplockage	
10	Gatun Lake to Atlantic Ocean	west lane	Downlockage	
11	Atlantic Ocean to Gatun Lake	east lane	Uplockage	
12	Gatun Lake to Atlantic Ocean	east lane	Downlockage	
13	Atlantic Ocean to Gatun Lake	new lane	Uplockage	wsb's out of use
14	Gatun Lake to Atlantic Ocean	new lane	Downlockage	wsb's out of use
15	Atlantic Ocean to Gatun Lake	new lane	Uplockage	wsb's in use
16	Gatun Lake to Atlantic Ocean	new lane	Downlockage	wsb's in use

Table 3.1 Ship movements in simulation model

A turn around scenario describes the operational steps during a so-called 'turn around' (a change from northbound ship transits in a lane to southbound ship transits or reverse). In a turn around the water levels in the lock chambers are prepared for the change in ship transit direction. A total number of 16 different turn arounds, including those for the future new lane, are distinguished in the simulation model (see Table 3.2).

no	*side of canal*	*turn around*	*lane*	*remarks*
1	Pacific side	change from northbound to southbound traffic	west lane	
2	Pacific side	change from southbound to northbound traffic	west lane	
3	Pacific side	change from northbound to southbound traffic	east lane	
4	Pacific side	change from southbound to northbound traffic	east lane	
5	Pacific side	change from northbound to southbound traffic	new lane	wsb's out of use
6	Pacific side	change from southbound to northbound traffic	new lane	wsb's out of use
7	Pacific side	change from northbound to southbound traffic	new lane	wsb's in use
8	Pacific side	change from southbound to northbound traffic	new lane	wsb's in use
9	Atlantic side	change from southbound to northbound traffic	west lane	
10	Atlantic side	change from northbound to southbound traffic	west lane	
11	Atlantic side	change from southbound to northbound traffic	east lane	
12	Atlantic side	change from northbound to southbound traffic	east lane	
13	Atlantic side	change from southbound to northbound traffic	new lane	wsb's out of use
14	Atlantic side	change from northbound to southbound traffic	new lane	wsb's out of use
15	Atlantic side	change from southbound to northbound traffic	new lane	wsb's in use
16	Atlantic side	change from northbound to southbound traffic	new lane	wsb's in use

Table 3.2 Turn arounds 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 3.3 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 lockage operations without a ship.

The vessels which use the new shipping lane, are represented by three additional vessel classes (see Table 3.4). 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 2.1.

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

3.5 Steps in scenarios for ship movements

In this section the various steps in scenarios for ship movements in the new lane with a two-lift lock system are described. A distinction is made between locks without wsb's and locks with wsb's.

3.5.1 Locks without wsb's

Next table shows the subsequent steps in the uplockage scenario 'ship movement Pacific Ocean → Gatun Lake':

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

Table 3.5 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks without wsb's

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 Q	(Density flows)
Forebay Lock Q	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	Tailbay Lock P	Equalize water levels
Lock P	Tailbay Lock P	Move ship

Table 3.6 Downlockage. Gatun Lake → Pacific Ocean. New lane, two-lift locks without wsb's.

The steps in the scenarios for ship movements Atlantic Ocean → Gatun Lake en Gatun Lake → Atlantic Ocean are similar, apart from the names of the locks (tailbay lock P = tailbay lock R, lock P = lock R, lock Q = lock S, forebay lock Q = forebay lock S).

3.5.2 Locks with wsb's

More steps are required in scenarios for ship movements in a three-lift lock system with wsb's. As an example next Table 3.7 shows the subsequent steps in the uplockage scenario 'ship movement Pacific Ocean → Gatun Lake' (see also Figure 3.5):

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

Table 3.7 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks with wsb.

The subsequent steps in the downlockage scenario 'ship movement Gatun Lake → Pacific Ocean' are shown in Table 3.8 (see also Figure 3.6):

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

Table 3.8 Downlockage. Gatun Lake → Pacific Ocean. New lane, two-lift locks with wsb's.

The steps in the scenarios for ship movements Atlantic Ocean → Gatun Lake and Gatun Lake → Atlantic Ocean are similar, apart from the names of the locks (tailbay lock P = tailbay lock R, lock P = lock R, lock Q = lock S, forebay lock Q = forebay lock S).

3.6 Steps in scenarios for turn arounds

A turn around scenario contains the various steps which are required to prepare the locks for a change in ship transit direction. The subsequent steps in turn arounds in the new lane with a two-lift lock system are described in this section. A distinction is made between locks without wsb's and locks with wsb's.

3.6.1 Locks without wsb's

As an example we present the steps in the 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 (see also Figure 2.1). The water level in lock P has to be lowered. Only one step is required:

Low basin	*High basin*	*Operation*
Tailbay Lock P	Lock P	Equalize water levels

Table 3.9 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage) transits. New lane, two-lift locks without wsb's.

The steps in the turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)' are shown in next table. 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. Water in the forebay of lock Q is exchanged with water in Gatun Lake (density flows).

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

Table 3.10 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage) transits. New lane, two-lift locks without wsb's.

Steps in turn arounds at the Atlantic side are similar, apart from the names of the locks (tailbay lock P = tailbay lock R, lock P = lock R, lock Q = lock S, forebay lock Q = forebay lock S).

3.6.2 Locks with wsb's

Locks with wsb's require more steps. As an example the steps in the turn around scenario 'Pacific side, change from northbound (uplockage) to southbound (downlockage)' are shown in Table 3.11. After passage of the last northbound ship (uplockage) the water levels in lock chambers P and Q are high and the wsb's are empty. The water level of lock P has to be lowered and the corresponding wsb's filled.

Low basin	*High basin*	*Operation*
Tailbay Lock P	Lock P	Fill wsb's of lock P
Tailbay Lock P	Lock P	Equalize water levels

Table 3.11 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage) transits. New lane, two-lift locks with wsb.

The steps in the turn around scenario 'Pacific side, change from southbound (downlockage) to northbound (uplockage)' are shown in Table 3.12. The water levels in lock chambers P and Q are low after passage of the last southbound ship (downlockage) and the wsb's are filled. The water level in lock chamber Q has to be raised and the corresponding wsb's emptied. Water in the forebay of lock Q is exchanged with water in Gatun Lake (density flows).

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

Table 3.12 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage) transits. New lane, two-lift locks with wsb.

Steps in turn arounds at the Atlantic side are similar, apart from the names of the locks (tailbay lock P = tailbay lock R, lock P = lock R, lock Q = lock S, forebay lock Q = forebay lock S).

3.7 Dimensions of locks, wsb's and forebays / tailbays

The characteristic dimensions of locks, wsb's and forebays in the new shipping lane are indicated in Table 3.13 (see also Figures 2.1 and 2.2).

basin	*nominal length*	*width*	*nominal, mean water level (m to PLD)*		*flooor level / sill level*	*step sill - sill*	*coping level*
	(m)	*(m)*	*high*	*low*	*(m to PLD)*	*(m to PLD)*	*(m to PLD)*
Pacific side							
Lock P	515	61	+13.11	+0.30	-21.22 / -20.62	13.13	+20.15
wsb's lock P					-0.99*		
Lock Q	515	61	+25.91	+13.11	-8.09 / -7.49	13.13	+31.60
wsb's lock Q					+12.70*		
Forebay Lock Q			+25.91		+5.03 / +5.64	+31.60	+29.67
Atlantic side							
Lock R	515	61	+12.99	+0.06	-19.28 /-18.67	12.15	+18.55
wsb's lock R					+0.95*		
Lock S	515	61	+25.91	+12.99	-7.13 /-6.52	12.16	+31.60
wsb's lock S					+13.65*		
Gatun S forebay			+25.91		+5.03 /+5.64		+31.60

*) floor level (lowest point) of lower wsb

Table 3.13 Dimensions of locks, wsb's and forebays, new shipping lane

The characteristic dimensions of locks and forebays / tailbays in the existing lanes are shown in Table 3.14.

basin	*nominal length* (m)	*width* (m)	*nominal, mean water level (m to PLD)* high	low	*floor level / sill level* (m to PLD)	*step sill - sill* (m)	*coping level* (m to PLD)
Pacific side							
Lock A (A-west & A-east)	329.2	33.5	+7.92	+0.30	-15.54 / -15.24	9.65	+9.75
Lock B (B-west & B-east	332.1	33.5	+16.46	+7.92	-6.20 / -5.59	9.04	+17.88
Forebay lock B (B-west & B-east)			+16.46		+3.35 (near intake) / +3.45		
Tailbay Lock C (C-west & C-east)			+16.46		+2.59 (near outlet) / +3.69		
Lock C (C-west & C-east)	332.1	33.5	+25.91	+16.46	+3.35 / +3.96	7.42	+28.04
Forebay lock C (C-west & C-east)			+25.91		+11.38 (near intake) / +11.38		
Atlantic side							
Lock D (D-west & D-east)	329.2	33.5	+8.54	+0.06	-13.51 / -12.90	8.76	+10.57
Lock E (E-west & E-east)	329.2	33.5	+17.38	+8.54	-4.67 / -4.14	8.71	+19.58
Lock F (F-west & F-east)	332.1	33.5	+25.91	+17.38	+4.17 / +4.57	6.81	+28.04
Forebay lock F (F-west & F-east)			+25.91		+4.27 (near intake) / +11.38		

Table 3.14 Dimensions of existing locks and forebays / tailbays

The dimensions and properties of basins in the simulation model are as follows:

New locks

The nominal lock chamber length is the size between the centre line of the downstream upper miter gates and the centre line of the downstream lower miter gates and equals about 515 m for all lock chambers. The nominal length multiplied by the chamber width and the water-level difference between adjacent chambers determines the quantity of lockage water that is transferred in downstream direction during uplockage or downlockage of a ship. This quantity includes both the volume of two gate recesses in the lock chamber (that has to be added) and the volume of the step in floor level (that has to be subtracted). Coping level corresponds to the top level of the lock walls.

Forebays new locks

The water volume of the forebays in Gatun Lake is arbitrarely computed as the product of length 515 m (= nominal lock chamber length), width 61 m (= lock chamber width) and water depth above the adjacent sill of the lock. In formula form:

$$V_{forebay} = A_{forebay} \,.\, (h_{lake} - f_{sill}) = 515 \text{ m} \,.\, 61 \text{ m} \,.\, (h_{lake} - f_{sill})$$

Water saving basins new locks

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

Existing locks

The nominal lock chamber length is the size between upper gate and lower gate of a lock This size determines the quantity of lockage water and is used in the simulations. Floor level corresponds to the flat, deeper part of the lock chambers; the sills protrude 0.3 m – 0.6 m (1 ft – 2 ft) above floor level. Lock chamber floors are thus at a lower elevation than the sills. Coping level corresponds to the top of the chamber walls.

Forebays and tailbays existing locks

The water volume of the forebays in Miraflores Lake and Gatun Lake and the tailbays in Miraflores Lake is arbitrarely computed as the product of length 330 m (= average nominal lock chamber length), width 33.5 m (= lock chamber width) and water depth above the adjacent lock sill. In formula form:

$$V_{forebay} = A_{forebay} \,.\, (h_{lake} - f_{sill}) = 330 \text{ m} \,.\, 33.5 \text{ m} \,.\, (h_{lake} - f_{sill})$$
$$V_{tailbay} = A_{tailbay} \,.\, (h_{lake} - f_{sill}) = 330 \text{ m} \,.\, 33.5 \text{ m} \,.\, (h_{lake} - f_{sill})$$

Function of forebays and taillbays 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.
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.

In the simulations we put:

lock chambers

V_{lock}	$= l_{lock} \cdot b_{lock} \cdot d_{lock}$ = water volume of lock chamber
l_{lock}	= nominal length of lock chamber; existing locks see Table 3.14, new locks 515 m
b_{lock}	= width of lock chamber (see Tables 3.13 and 3.14)
h_{lock}	= water level (in m to PLD)
f_{lock}	= floor level (in m to PLD; see Tables 3.13 and 3.14)
d_{lock}	= water depth in lock chamber = $h_{lock} - f_{lock}$
$maxh_{lock}$	= highest water level in lock chamber = coping level (in m to PLD)
$minh_{lock}$	= lowest water level in lock chamber; existing locks: sill level + 10 m (in m to PLD); new locks: floor level + 10 m (in m to PLD)

forebays (Gatun Lake, Miraflores Lake) and tailbays (Miraflores Lake) existing locks

$V_{forebay}$	$= 330 \text{ m} \cdot 33.5 \text{ m} \cdot (h_{lake} - f_{sill})$
$V_{tailbay}$	$= 330 \text{ m} \cdot 33.5 \text{ m} \cdot (h_{lake} - f_{sill})$

forebays new locks (Gatun Lake)

$V_{forebay}$	$= 515 \text{ m} \cdot 61 \text{ m} \cdot (h_{lake} - f_{lock})$

water saving basins new locks

V_{wsb}	$= l_{wsb} \cdot b_{wsb} \cdot d_{wsb}$
l_{wsb}	= length of wsb in simulation = 515 m
b_{wsb}	= width of wsb in simulation = 61 m
d_{wsb}	= water depth of wsb (total depth of the three individual wsb's)
$maxV_{wsb}$	= maximum water volume of wsb; about 20 m x 515 m x 61 m (650000 m^3)
$minV_{wsb}$	= minimum water volume in wsb = 0.01 * $maxV_{wsb}$ (6500 m^3 corresponding to about 0.2 m water depth)

3.8 Miraflores Lake and Gatun Lake

3.8.1 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 were 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.
The same water levels are used as input in the simulation model for the new situation, after realization of the new shipping lane. The average water level values are shown in next table together with the corresponding water volume.

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 3.15 Gatun Lake: representative water level and corresponding water volume

The water levels of Gatun Lake and Miraflores Lake which are used in the simulation model are shown in Figure 3.7.

3.8.2 Water releases

The water levels of Miraflores Lake and Gatun Lake are controled by spillways. When the water level exceeds a maximum value, the surplus water is spilled. Water of Gatun Lake is also used for hydropower generation, water of Miraflores Lake for cooling.

The daily spilled water quantities of Gatun Lake and water quantities used for hydropower generation have been averaged for all months in the period 1992 – 2001. The average values of month-averages (January, February, ... December) in this period were used in the validation of the simulation model (existing situation, see Report A); they were regarded as typical, representative values. Since the locks on the new shipping lane cause extra water losses, 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.

In a *baseline scenario* we start from the assumption that all extra water losses from Gatun Lake caused by the new locks are compensated by an equal quantity of fresh water, that is supplied from new water sources. Consequently, the present water levels and water releases will not change and we will use the representative water-release quantities presented in Table 3.16 as input in the simulation model.

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 3.16 Gatun Lake: representative values of daily spilled water quantities and water quantities used for hydropower (baseline scenario)

In a *second scenario* we assume that the extra water losses caused by 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. The extra water losses of the new locks are growing when the Post-Panamax shipping increases. Table 3.17 presents the extra water losses of the new locks in this scenario; the values are based on the ship-traffic projections of ACP for the next 50 years (semi-convoy mode of operation) and on the assumption of 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 / 2) m * 515 m * 61 m * 2 = about 8.10^5 m^3 (when wsb's are in use with 50% water saving rate the water loss amounts to 4.10^5 m^3).

Period after opening of new lane	*Post-Panamax ship transits (number per day)*	*Extra water losses (10^6 m^3/day)*	*Extra water losses in case of wsb's (10^6 m^3/day)*
month 1	2	1.60	0.80
year 1	5	4.00	2.00
year 5	6	4.80	2.40
year 10	7	5.60	2.80
year 20	9	7.20	3.60
year 50	15	12.00	6.00

Table 3.17 Extra water losses after opening of third, new lane

In the *second scenario* the water releases at Gatun Dam are as follows (reduction for extra water losses of new lane included):

Month	*Total water release year 0 (10^6 m^3 per day)*	*Total water release month 1 (10^6 m^3 per day)*	*Total water release year 1 (10^6 m^3 per day)*	*Total water release year 5 (10^6 m^3 per day)*	*Total water release year 10 (10^6 m^3 per day)*	*Total water release year 20 (10^6 m^3 per day)*	*Total water release year 50 (10^6 m^3 per day)*
January	4.61	3.01	0.61	0.00	0.00	0.00	0.00
February	0.60	0.00	0.00	0.00	0.00	0.00	0.00
March	0.20	0.00	0.00	0.00	0.00	0.00	0.00
April	0.16	0.00	0.00	0.00	0.00	0.00	0.00
May	0.94	0.00	0.00	0.00	0.00	0.00	0.00
June	3.63	2.03	0.00	0.00	0.00	0.00	0.00
July	5.55	3.95	1.55	0.75	0.00	0.00	0.00
August	6.58	4.98	2.58	1.78	0.98	0.00	0.00
September	8.32	6.72	4.32	3.52	2.72	1.12	0.00
October	8.23	6.63	4.23	3.43	2.63	1.03	0.00
November	11.60	10.00	7.60	6.80	6.00	4.40	0.00
December	12.63	11.03	8.63	7.83	7.03	5.43	0.63

Table 3.18 Gatun Lake: representative values of daily released water quantities (second scenario; locks in new lane without wsb's)

When the wsb's of the locks in the new lane are active the water losses are smaller and the water releases at Gatun Dam become:

Month	*Total water release year 0 (10^6 m^3 per day)*	*Total water release month 1 (10^6 m^3 per day)*	*Total water release year 1 (10^6 m^3 per day)*	*Total water release year 5 (10^6 m^3 per day)*	*Total water release year 10 (10^6 m^3 per day)*	*Total water release year 20 (10^6 m^3 per day)*	*Total water release year 50 (10^6 m^3 per day)*
January	4.61	3.81	2.61	2.21	1.81	1.01	0.00
February	0.60	0.00	0.00	0.00	0.00	0.00	0.00
March	0.20	0.00	0.00	0.00	0.00	0.00	0.00
April	0.16	0.00	0.00	0.00	0.00	0.00	0.00
May	0.94	0.14	0.00	0.00	0.00	0.00	0.00
June	3.63	2.83	1.63	1.23	0.83	0.03	0.00
July	5.55	4.75	3.55	3.15	2.75	1.95	0.00
August	6.58	5.78	4.58	4.18	3.78	2.98	0.58
September	8.32	7.52	6.32	5.92	5.52	4.72	2.32
October	8.23	7.43	6.23	5.83	5.43	4.63	2.23
November	11.60	10.80	9.60	9.20	8.40	8.00	5.60
December	12.63	11.83	10.63	10.23	9.83	9.03	6.63

Table 3.19 Gatun Lake: representative values of daily released water quantities (second scenario; locks in new lane with wsb's)

The daily water-release quantities of Tables 3.18 and 3.19 are used in the simulations.

The daily spilled water quantities of Miraflores Lake and the water quantities used for cooling at Miraflores are shown in Table 3.20. 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 3.20 Miraflores Lake: daily spilled / used water quantities in 2001

The values in Table 3.20 are not suited for use in the simulation model, because they are not representative for a longer period of time. To get better 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 3.21; these values are regarded as representative values and are used in the simulation model. Since the new lane does not effect the water level of Miraflores Lake the water release quantities are valid both for the *baseline scenario* and the *second scenario*.

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 3.21 Miraflores Lake: representative quantities of daily spilled water and water used for cooling (baseline scenario and second scenario)

The daily water releases of Gatun Lake and Miraflores Lake are shown in Figure 3.8 (baseline scenario).

3.8.3 Effect of water level changes and water releases

Water levels and corresponding water volumes of Gatun Lake and Miraflores Lake are prescribed for each day of a case in the simulation model. Also the water-release quantities are prescribed through special water-release scenarios in the day pattern. The effects of water level changes on the salt concentration of the lakes are evaluated at the start of each day; the effects of water releases are evaluated when the water-release scenarios are executed (see also Section 4.6).

3.9 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 it are the period and the amplitude that count, rather than a full reproduction of the 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 3.9).

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 3.10).

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 3.22 Salt concentration in tailbays at Pacific and Atlantic side

The salt concentrations presented in the above table are also shown in Figure 3.11.

3.10 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. In addition, an initial value must be given to the salt concentrations in the lock chambers and wsb's, 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. Initial water levels in the lock chambers are by default selected from Tables 3.13 and 3.14 (nominal, mean high water level); initial water volumes of wsb's are by default set to '$minV_{wsb}$' (see Section 3.7).

4 Evaluation of nodal status parameters

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.
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, see Section 3.10. 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 Section 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, 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. 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 equations for ship movements and turn arounds in the *existing* shipping lanes are explained in Report A; they will not be repeated here.

4.1 Ship movements new lane, two-lift locks without wsb's

The evaluation of nodal status parameters for ship movements in the new shipping lane provided with a two-lift lock system without wsb's, is similar as described in Report A. Reference is made to Report A for a description.

4.2 Ship movements new lane, two-lift locks with wsb's, uplockage

Two 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

The time-dependent exchange of salt water between forebays / tailbays and lakes is handled in a 'special step'.

For the various combinations of basins (tailbays, locks with wsb's, forebays, lakes) the equations which describe the water balance and the salt balance within a basic step of the locking process are presented.

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

- the water volume V_{save} that is spilled to and supplied from the wsb's of adjacent locks is equal to maximum 50% of the water volume V_{ref} that would be exchanged between these locks when no wsb's were present
- 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
- the same starting points hold when low basin is tailbay and high basin is lock, or when low basin is lock and high basin is forebay.

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:

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

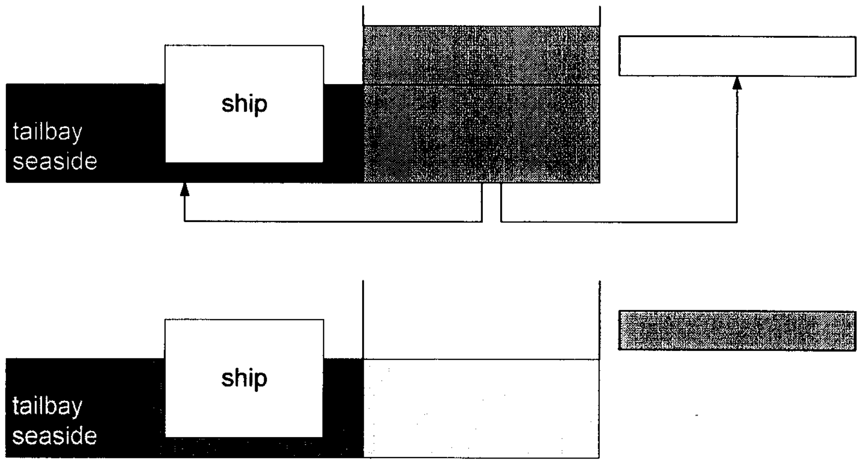
with: e_{x0} = value of e_x for S = 0

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 that is filled, and salt withdrawal from the wsb 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

step I: the water level in the low basin (with ship) is equalized with the water level in the high basin (without ship); water is transferred from high basin to low basin; if relevant: the wsb's of the lower lock are emptied, the wsb's of the higher lock are filled

low basin = tailbay seaside, high basin = lock



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

$V_{save} = 0.5 \cdot V_{ref}$
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$
check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$

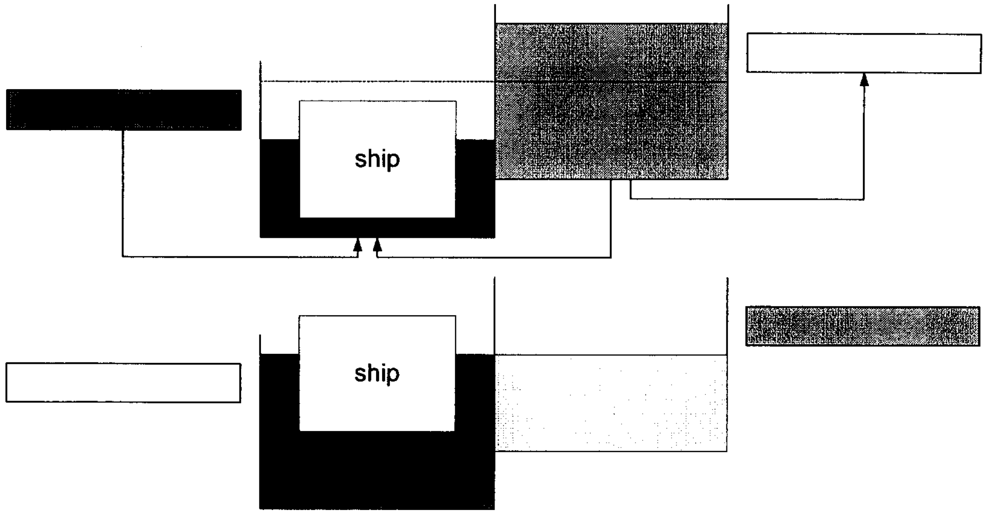
salt balance

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 = lock



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsbhigh1}$, $V_{wsblow1}$

$$h_{low2} = h_{low1} + \frac{A_{high} \cdot (h_{high1} - h_{low1})}{(A_{low} + A_{high})}$$

check: $h_{low2} > maxh_{low}$?
    if yes: $h_{low2} = maxh_{low}$

$h_{high2} = h_{low2}$

check: $h_{high2} < minh_{high}$?
    if yes: $h_{high2} = minh_{high}$
        $h_{low2} = h_{high2}$

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

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

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

$V_{high2} = d_{high2} \cdot A_{high}$

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

$V_{save} = 0.5 \cdot V_{ref}$

$V_{wsblow2} = V_{wsblow1} - V_{save}$

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

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

check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
    if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
        $V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$
        $V_{wsblow2} = V_{wsblow1} - V_{save}$

salt balance

Known values at the beginning of step: c_{high1}, c_{low1}, $c_{wsbhigh1}$, $c_{wsblow1}$

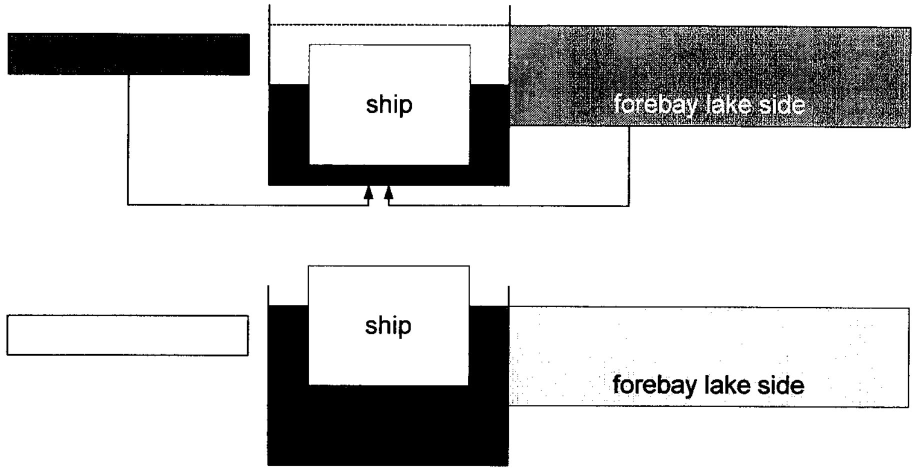
$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1}) + (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1})}{V_{low2}}$$

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

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

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

low basin = lock, high basin = forebay lake side



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
$h_{high2} = h_{high1} = h_{lake}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = (d_{low2} \cdot A_{low}) - S$
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{save} = 0.5 \cdot V_{ref}$
$V_{wsblow2} = V_{wsblow1} - V_{save}$
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}, $c_{wsblow1}$

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

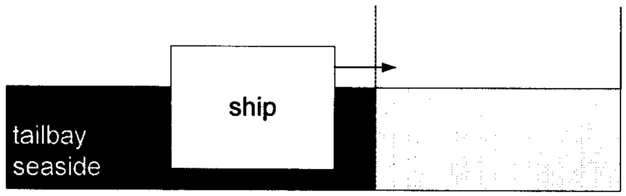
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

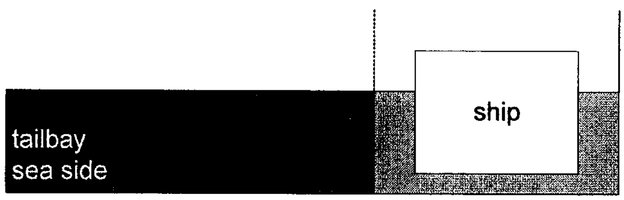
$$c_{wsblow2} = \frac{(V_{wsblow1} \cdot c_{wsblow1}) - (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1})}{V_{wsblow2}}$$

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

step II: the 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

low basin = tailbay sea side, high basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}

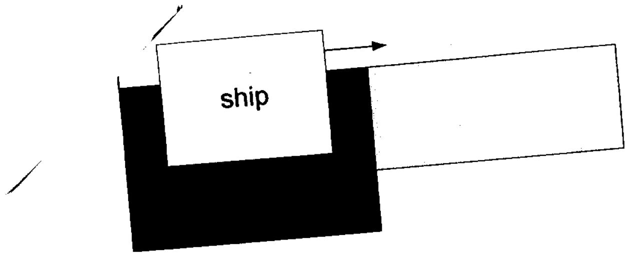
$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1}$$
$$V_{high2} = V_{high1} - S$$
$$V_{ref} = V_{high1}$$

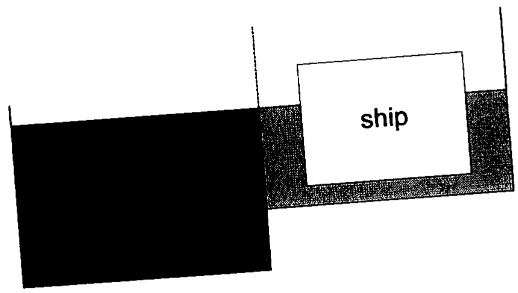
salt balance

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

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

‹n = lock, high basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{low2} = h_{low1}$
$d_{low2} = d_{low1}$
$V_{low2} = V_{low1} + S$
$h_{high2} = h_{high1}$
$d_{high2} = d_{high1}$
$V_{high2} = V_{high1} - S$
$V_{ref} = V_{high1}$

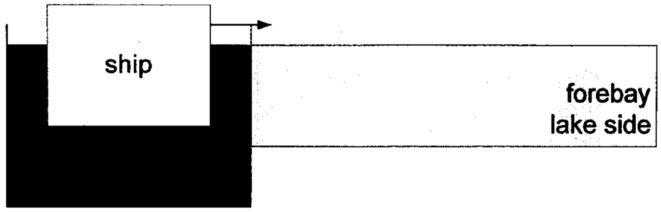
salt balance

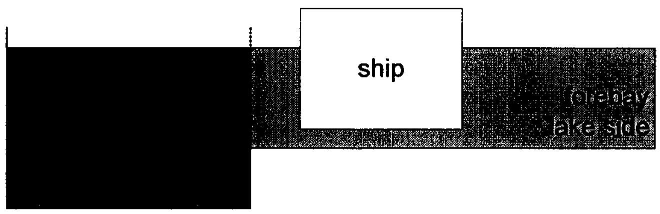
Known values at the beginning of step: c_{high1}, c_{low1}

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

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

low basin = lock, high basin = forebay lake side





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$$h_{low2} = h_{low1}$$
$$d_{low2} = d_{low1}$$
$$V_{low2} = V_{low1} + S$$
$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1} = d_{forebay}$$
$$V_{high2} = V_{high1} = V_{forebay}$$
$$V_{ref} = V_{high1}$$

salt balance

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

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

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

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

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 an uplocking ship has passed the forebay or after a turn around the salt concentration in the forebay has changed. Density differences exist between the water in the forebay and the water in the lake, and as a result density-driven exchange flows occur. 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. 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}	= 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

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull} = 1$.
A period T = 3600 s is selected for the forebays in Gatun Lake starting from the assumption that the propagation velocity of a salt tongue is in the order of 0.1 – 0.2 m/s.

4.3 Ship movements new lane, two-lift locks with wsb's, downlockage

Two 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

The time-dependent exchange of salt water between forebays / tailbays and lakes is handled in a 'special step'.
For the various combinations of basins (tailbays, locks with wsb's, forebays) the equations which describe the water balance and the salt balance within a basic step of the locking process are presented.

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

- the water volume V_{save} that is spilled to and supplied from the wsb's of adjacent locks is equal to maximum 50% of the water volume V_{ref} that would be exchanged between these locks when no wsb's were present
- 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
- the same starting points hold when low basin is tailbay and high basin is lock, or when low basin is lock and high basin is forebay.

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:

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

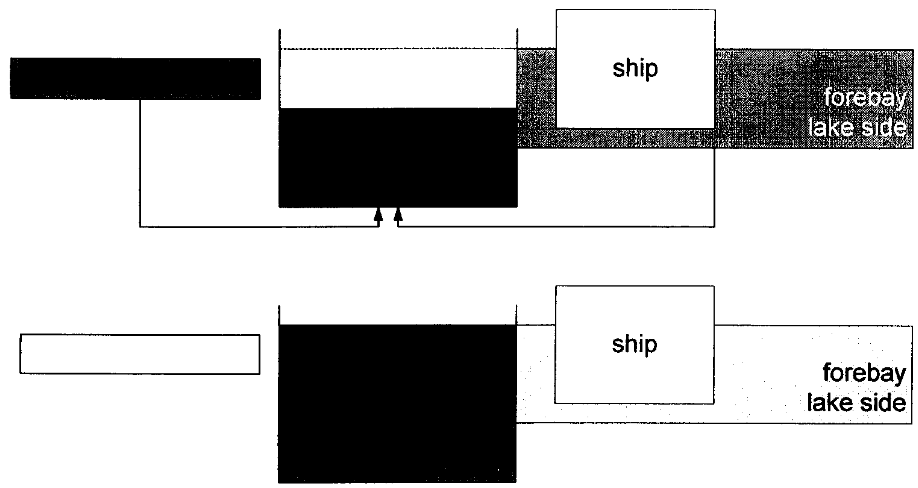
with: e_{x0} = value of e_x for S = 0

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 that is filled, and salt withdrawal from the wsb 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

step I: the water level in the low basin (without ship) is equalized with the water level in the high basin (with ship) ; water is transferred from high basin to low basin; if relevant: the wsb's of the lower lock are emptied, the wsb's of the higher lock are filled

high basin = forebay lake side, low basin = lock



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
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{save} = 0.5 \cdot V_{ref}$
$V_{wsblow2} = V_{wsblow1} - V_{save}$
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}, $c_{wsblow1}$

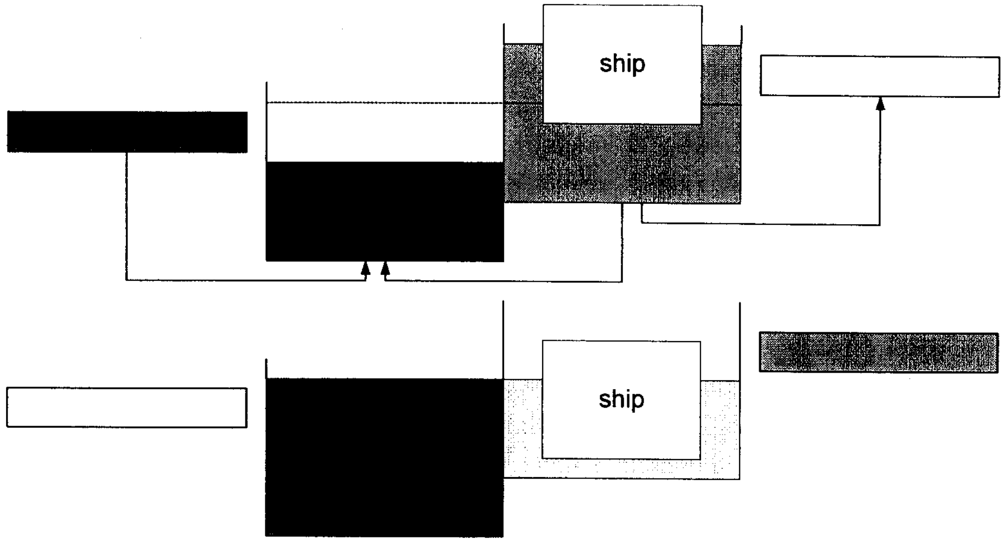
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

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

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

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

high basin = lock, low basin = lock



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsbhigh1}$, $V_{wsblow1}$

$$h_{high2} = h_{high1} - \frac{A_{low} \cdot (h_{high1} - h_{low1})}{(A_{low} + A_{high})}$$

check: $h_{high2} < minh_{high}$?
if yes: $h_{high2} = minh_{high}$

$h_{low2} = h_{high2}$

check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
$h_{high2} = h_{low2}$

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

$V_{high2} = (d_{high2} \cdot A_{high}) - S$

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

$V_{low2} = d_{low2} \cdot A_{low}$

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

$V_{save} = 0.5 \cdot V_{ref}$

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

check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$

$V_{wsblow2} = V_{wsblow1} - V_{save}$

check: $V_{wsblow2} < minV_{wsblow}$?
if yes: $V_{wsblow2} = minV_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$

salt balance

Known values at the beginning of step: c_{high1}, c_{low1}, $c_{wsbhigh1}$, $c_{wsblow1}$

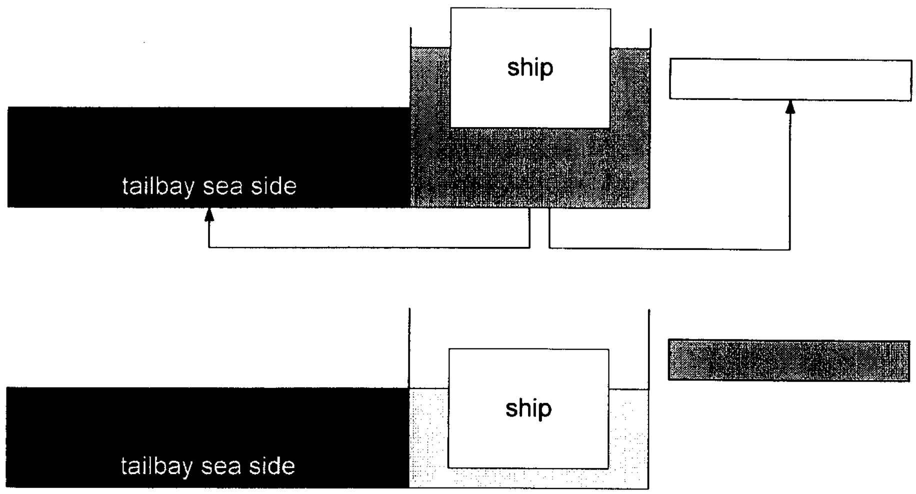
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_{wsbfill} \cdot V_{save} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1})}{V_{high2}}$$

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

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

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

high basin = lock, low basin = tailbay sea



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

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

$V_{high2} = d_{high2} \cdot A_{high} - S$

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

$V_{save} = 0.5 \cdot V_{ref}$

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

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

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

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

salt balance

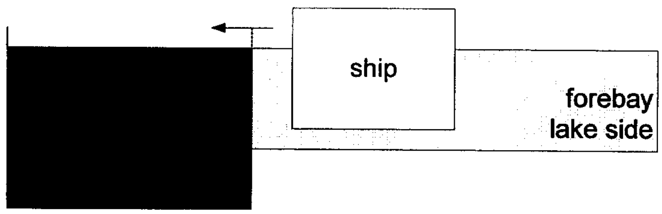
Known value at the beginning of step: c_{high1}, $c_{wsbhigh1}$

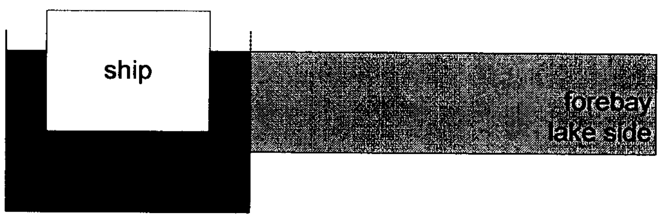
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_{wsbfill} \cdot V_{save} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1})}{V_{high2}}$$

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

step II: the 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

high basin = forebay lake side, low basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1} = d_{forebay}$$
$$V_{high2} = V_{high1} = V_{forebay}$$
$$h_{low2} = h_{low1}$$
$$d_{low2} = d_{low1}$$
$$V_{low2} = V_{low1} - S$$
$$V_{ref} = V_{high2} = V_{forebay}$$

salt balance

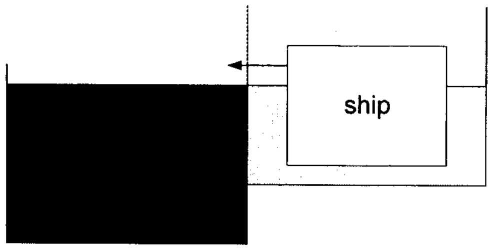
Known values at the beginning of step: c_{high1} ($= c_{forebay1}$), c_{low1}, c_{lake1}

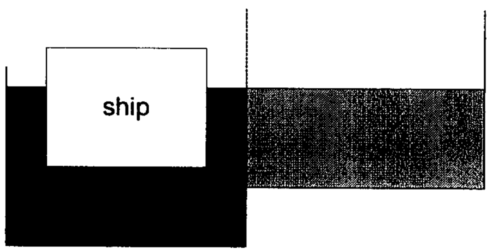
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) + e_x \cdot V_{ref} \cdot (c_{low1} - c_{high1}) + (S \cdot c_{low1}) - (S \cdot c_{high1})}{V_{high2}} = c_{forebay2}$$

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

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

high basin = lock, low basin = lock





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{high2} = h_{high1}$
$d_{high2} = d_{high1}$
$V_{high2} = V_{high1} + S$
$h_{low2} = h_{low1}$
$d_{low2} = d_{low1}$
$V_{low2} = V_{low1} - S$
$V_{ref} = V_{high2}$

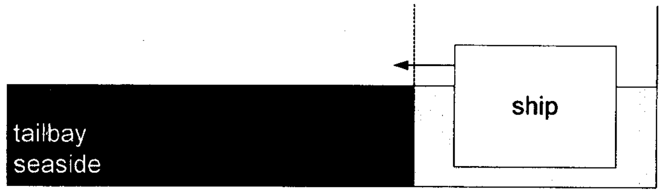
salt balance

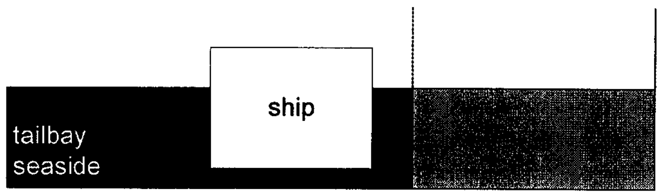
Known values at the beginning of step: c_{high1}, c_{low1}

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

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

high basin = lock, low basin = tailbay seaside





water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}

$$h_{high2} = h_{high1}$$
$$d_{high2} = d_{high1}$$
$$V_{high2} = V_{high1} + S$$
$$V_{ref} = V_{high2}$$

salt balance

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

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

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. Density differences exist between the water in the forebay and the water in the lake, and as a result density-driven exchange flows occur. 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 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. 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}	= 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

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull} = 1$.
A period T = 3600 s is selected for the forebays in Gatun Lake starting from the assumption that the propagation velocity of a salt tongue is in the order of 0.1 – 0.2 m/s.

4.4 Turn arounds new lane, two-lift locks without wsb's

The evaluation of nodal status parameters in scenarios for turn arounds in the new shipping lane provided with a two-lift lock system without wsb's, is similar as described in Report A for the existing Miraflores Locks (Pacific side of the Panama Canal). Reference is made to Report A for a description.

4.5 Turn arounds new lane, two-lift locks with wsb's

4.5.1 Turn around Pacific side; change from northbound (uplockage) to southbound (downlockage) transits

After the last northbound vessel has passed the locks (uplockage), the water levels in lock chambers P and Q are high (see also Figure 2.1) and the wsb's are empty. The water level of lock P has to be lowered and the corresponding wsb's filled. The equations which describe the water balance and the salt balance for these actions are similar as described in Section 4.2, uplockage, step I (submerged volume S of ship = 0). In next table reference is made to the relevant case of this section.

Low basin	*High basin*	*Operation*	*Section 4.2, uplockage, step I* *Case*
Tailbay Lock P	Lock P	Fill wsb's of lock P	low basin = tailbay seaside,
Tailbay Lock P	Lock P	Equalize water levels	high basin = lock

Table 4.1 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage) transits. New lane, two-lift locks with wsb.

4.5.2 Turn around Pacific side; change from southbound (downlockage) to northbound (uplockage) transits

The water levels in lock chambers P and Q are low after passage of the last southbound ship (downlockage) and the wsb's are filled. The water level in locks Q has to be raised and the corresponding wsb's emptied. The equations which describe the water balance and the salt balance for these actions are similar as described in Section 4.3, downlockage, step I (submerged volume S of ship = 0). In next table reference is made to the relevant cases of this section. The actions are concluded with the special step described at the end of Section 4.3.

High basin	*Low basin*	*Operation*	*Section 4.3, downlockage, step I Case*
Forebay Lock Q	Lock Q	Empty wsb's of lock Q	high basin = lock,
Forebay Lock Q	Lock Q	Equalize water levels	low basin = tailbay seaside
Gatun Lake	Forebay Lock Q	(Density flows)	special step of Section 4.3

Table 4.2 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage) transits. New lane, three-lift locks with wsb.

4.5.3 Turn arounds Atlantic side

Steps in turn-arounds scenarios for the Atlantic side are similar as steps in turn-around scenarios for the Pacific side, apart from the names of the locks (tailbay lock P = tailbay lock R, lock P = lock R, lock Q = lock S, forebay lock Q = forebay lock S) and the north – south orientation.

4.6 Effect of water level changes of lakes and water releases

The water levels and corresponding water volumes of Gatun Lake and Miraflores Lake form input for the simulation model. The effect of water releases from the lakes on the water volumes is implied in the water levels, which are prescribed in the input table. The effect of water level changes of the lakes on the salt concentration is evaluated at the start of each day in the simulation.
Water releases (spillage of surplus water through Gatun Spillway and Miraflores Spillway, water for power generation, water for cooling) are prescribed through the water-release scenarios. The effect of the water releases on the salt concentration of the lakes is evaluated in the simulation, at the moment of time when the water-release scenarios are executed.

For a description of the evaluation of the effects of water level changes and water releases on the salt concentration of the lakes, reference is made to Report A.

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 that will be used in the simulation model for the future situation are selected on the experiences with the existing situation and on Delft3D density-flow computations.

5.1 Exchange coefficients when wsb's are in use

5.1.1 Delft3D computations

We have executed Delft3D computations for the filling and emptying process in a lock chamber and for the density-flow phenomena related to ship movements from one lock chamber to another, from forebay to lock chamber and from lock chamber to forebay and reverse. This kind of computations was done for locks in the existing situation and for the 1-lift and three-lift lock configurations of Post-Panamax Locks.

The floor filling and emptying system of the two-lift lock configuration of Post-Panamax Locks is similar to the floor filling and emptying system of the existing locks. As we have seen (see Report B and Report C for reference) the hydraulic phenomena during filling and emptying of the chambers of the single-lift and three-lift locks, which are provided with a wall filling and emptying system with openings at floor level, have a strong mutual resemblance, but have also a strong resemblance with the phenomena in the existing three-lift locks.
The main conclusions are: Filling of a lock chamber through the openings in the lock chamber walls or through the openings in the lock chamber floor causes a mixing up of the full water body in the chamber, also when a ship is present in the chamber. After filling the salt concentration distribution in the lock chamber is rather uniform, but the highest concentration is present near the floor. When the lock chamber is emptied through the wall openings or through the floor openings, the water is mainly drawn from the lower water area and the vertical distribution of the salt concentration of the remaining water volume does not change much; the water in the lock chamber is hardly mixed up during emptying.
From these observations we can assume that the hydraulic phenomena in the lock chambers of the two-lift lock system will not be different during filling or emptying.

A ship moving from one basin to another causes exchange flows while also density flows develop. Exchange flows and density flows caused by ship movements between tailbay and lower lock are similar in 1-lift, 2-lift and 3-lift lock configurations, because of the identical geometry of tailbay and lower lock. Exchange flows and density flows caused by ship movements between adjacent locks or between upper lock and forebay have a high resemblance at all three lock configurations, but, generally, a smaller step in the floor causes a greater salt water intrusion.

Delft3D computations (2DV approach) have been made of the density flow between lower and upper lock chamber in the case of a density difference. The exchange flows and density flows caused by a moving ship have also been simulated. Dimensions of the ship: ship type VII, Post-Panamax, draught 14 m, see Section 3.4.
The results of the Delft3D computations are discussed for the configuration 'lower lock – upper lock'. Water depth in lower chamber 32.6 m, in upper chamber 20 m; initial salt concentration in the lower chamber 10 ppt, in the upper chamber 2 ppt. Figure 5.1 shows the results for the density flows when no ship is present; the results for an uplocking ship are shown in Figure 5.2, and the results for a downlocking ship are shown in Figure 5.3.
The figures present the volume-averaged salt concentration in upper and lower chamber as a function of time. The density-flow phenomena have also been made visible by means of a 'snap shot' movie.

Exchange flows
Results of the Delft3D computation are shown in Figure 5.1. The 'snap shot' movie shows that a salt tongue enters the upper chamber over the floor; simultaneously water with lesser salinity enters the lower chamber near the water surface. Both tongues reflect against the closed sides of the chambers. The internal waves damp out only very slowly; mixing does hardly not occur. The volume-averaged salt concentration decreases (lower lock) or increases (upper lock) lineair as a function of time. Also the exchange coefficient e_x increases more or less lineair as a functio of time.

Uplockage
The computation with a Post-Panamax ship (ship type VII, see results in Figure 5.2) moving from lower chamber to upper chamber shows that the intrusion of salt water into the upper chamber is to a considerable extent prevented by the return current of the ship. From the 'snap shot' movie it appears that most salt water enters the upper lock after the ship has entered the upper lock. This is also shown in Figure 5.2: the salt concentration in the upper lock remains more or less constant during movement of the ship, while the concentration of the lower lock decreases because of the return flow of the ship (the ships volume is replaced by water from the upper lock with lesser salinity). The salt exchange coefficient e_x shown in Figure 5.2 is related to the initial volume of the upper lock in the simulation model (see Section 4.2), is almost nill during movement of the ship and increases to a value of about 0.10 after 15 minutes.

Downlockage
In the case that a ship moves from upper lock to lower lock the return current sustains the intrusion of salt water into the upper lock. Saltier water from the lower lock is forced to flow into the upper lock, but the involved water originates for the greater part from the water body above the level of the step, as is demonstrated by the 'snap shot' movie. Internal waves occur in the lock chambers, but do not cause important mixing. Figure 5.3 indicates that the volume-averaged salt concentration of the upper lock increases during movement of the ship, while the salt concentration of the lower locks remains more or less constant, which means that the ship's volume is replaced with saltier water from the lower lock. The exchange coefficient e_x shown in Figure 5.3 is related to the final volume of the upper lock (see Section 4.3) and increases to a value of 0.10 after 15 minutes.

5.1.2 Selection of exchange coefficients

On the basis of the results of the earlier Delft3D computations for 1-lift and 3-lift locks and the insights obtained in the hydraulic processes, we select next exchange coefficients for step I of the lockage process ('equalize water levels') in the 2-lift locks:

uplockage

fill wsb of upper lock:	$e_{fillwsb}$	= 1.3
empty wsb of lower lock:	$e_{emptywsb}$	= 1.0
equalize water levels:	e_x	= 1.15 (for lock-forebay combination: 0.95)

downlockage

fill wsb of lower lock:	$e_{fillwsb}$	= 1.15
empty wsb of upper lock:	$e_{emptywsb}$	= 1.0
equalize water levels:	e_x	= 1.15 (for forebay-lock combination: 0.85)

The exchange coefficient for step II (' movement of ship') are selected on the basis of the results of Delft3D computations and after a careful comparison with the exchange coefficients which were selected for the 1-lift and 3-lift lock configurations. The exchange coefficients are dependent on the ship volume S (see Chapter 4). Next representative values of e_x are valid for S = 0:

uplockage

movement tailbay → lower lock:	e_x	= 0.7 (similar as for 1-lift and 3-lift locks)
movement lower lock → upper lock:	e_x	= 0.05
movement upper lock → forebay:	e_x	= 0.0

downlockage

movement forebay → upper lock:	e_x	= 0.1
movement upper lock → lower lock:	e_x	= 0.15
movement lower lock → tailbay:	e_x	= 0.4 (similar as for 1-lift and 3-lift locks)

It will be clear that uncertainties exists in the choice of representative exchange coefficients. For that reason we have executed a sensitivity analysis, in which we have varied the coefficients for step I and step II of the lockage process (see Section 7.4).

An overview of selected exchange coefficients for the 2-lift locks with wsb's at the Pacific side is presented in Tables 5.1 and 5.2. Equal exchange coefficients are selected for the 2-lift locks at the Atlantic side.

The combinations of exchange coefficients, which were varied in the sensitivity analysis, are also shown in the tables under Sens1 – Sens4.

Low basin	*High basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Tailbay Lock P	Lock P	Fill wsb's of lock P	1.3			1.0	1.5
Tailbay Lock P	Lock P	Equalize water levels	1.15			1.0	1.5
Tailbay Lock P	Lock P	Move ship	0.7*	0.5*	0.9*		
Lock P	Lock Q	Empty wsb's of lock P	1.0				
Lock P	Lock Q	Fill wsb's of lock Q	1.3			1.0	1.5
Lock P	Lock Q	Equalize water levels	1.15			1.0	1.5
Lock P	Lock Q	Move ship	0.05*	0.0*	0.15*		
Lock Q	Forebay Lock Q	Empty wsb's of lock Q	1.0				
Lock Q	Forebay Lock Q	Equalize water levels	0.95			0.7	1.2
Lock Q	Forebay Lock Q	Move ship	0.0*	0.0*	0.1*		
Forebay Lock Q	Gatun Lake	(Density flows)	1.0**				

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

Table 5.1 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks with wsb.

High basin	*Low basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Gatun Lake	Forebay Lock Q	(Density flows)	1.0**				
Forebay Lock Q	Lock Q	Empty wsb's of lock Q	1.0				
Forebay Lock Q	Lock Q	Equalize water levels	0.85			0.6	1.1
Forebay Lock Q	Lock Q	Move ship	0.10*	0.0*	0.2*		
Lock Q	Lock P	Fill wsb's of lock Q	1.15			1.0	1.4
Lock Q	Lock P	Empty wsb's of lock P	1.0				
Lock Q	Lock P	Equalize water levels	1.15			1.0	1.4
Lock Q	Lock P	Move ship	0.15*	0.05*	0.25*		
Lock P	Tailbay Lock P	Fill wsb's of lock P	1.15			1.0	1.4
Lock P	Tailbay Lock P	Equalize water levels	1.15			1.0	1.4
Lock P	Tailbay Lock P	Move ship	0.4*	0.3*	0.5*		

*) 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 5.2 Downlockage. Gatun Lake → Pacific Ocean. New lane, two-lift locks with wsb.

5.2 Exchange coefficients when wsb's are not in use

In the case that the wsb's of the new locks are not in use the full quantity of lockage water is spilled from the upper lock into the lower lock and than from the lower lock into the tailbay and in a next cycle replenished by water drawn from the forebay. The exchange coefficients for spillage (equalize water levels) are such selected that they have a similar effect on the remaining water in a lock chamber as in the case that wsb's are in use. For the withdrawal of water from the forebay we apply an equal exchange coefficient as in the case that the wsb's are in use. The other exchange coefficients in step I and step II of the lockage process remain the same.

An overview of selected exchange coefficients for the 2-lift locks at the Pacific side is presented in Tables 5.3 and 5.4. Equal exchange coefficients are selected for the 2-lift locks at the Atlantic side. The combinations of exchange coefficients that are varied in the sensitivity analysis are also shown under Sens1 – Sens4 (see Section 7.4).

Low basin	*High basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Tailbay Lock P	Lock P	Equalize water levels	1.25			1.0	1.5
Tailbay Lock P	Lock P	Move ship	0.7*	0.5*	0.9*		
Lock P	Lock Q	Equalize water levels	1.25			1.0	1.5
Lock P	Lock Q	Move ship	0.05*	0.0*	0.15*		
Lock Q	Forebay Lock Q	Equalize water levels	0.95			0.7	1.2
Lock Q	Forebay Lock Q	Move ship	0.0*	0.0*	0.1*		
Forebay Lock Q	Gatun Lake	(Density flows)	1.0**				

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

Table 5.3 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks without wsb.

High basin	*Low basin*	*Operation (Remarks)*	e_x	e_x *Sens1*	e_x *Sens2*	e_x *Sens3*	e_x *Sens4*
Gatun Lake	Forebay Lock Q	(Density flows)	1.0**				
Forebay Lock Q	Lock Q	Equalize water levels	0.85			0.6	1.1
Forebay Lock Q	Lock Q	Move ship	0.1*	0.0*	0.2*		
Lock Q	Lock P	Equalize water levels	1.15			1.0	1.4
Lock Q	Lock P	Move ship	0.15*	0.05*	0.25*		
Lock P	Tailbay Lock P	Equalize water levels	1.15			1.0	1.4
Lock P	Tailbay Lock P	Move ship	0.4*	0.3*	0.5*		

*) 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 5.4 Downlockage. Gatun Lake → Pacific Ocean. New lane, two-lift locks without wsb.

Equal exchange coefficients are selected for the locks at the Atlantic side.

5.3 Other exchange coefficients

The exchange coefficients for the locks in the existing shipping lanes do not change after opening of the new, third shipping lane (for values of the exchange coefficients reference is made to Report A).

We also assume that the exchange coefficients related to the release of water at Gatun Dam and Miraflores are uneffected by the new shipping lane. The values of these exchange coefficients have been selected on the basis of validation runs for the existing situation (see report A). Maintaining equal exchange coefficients for the release of water offers also the possibility of a direct analysis of the third-lane related inflow of salt water into the lakes.

6 Testing of simulation model

The salt-intrusion simulation model of the existing situation has been extended with the two-lift locks in the new lane. The extension required the adaptation of formula in view of the water saving basins of the new locks, the definition of extra scenarios for ship movements and turn arounds, the definition of new Post-Panamax ship types, 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.

Input data

Day Pattern	*Scenarios in day Pattern*	*Lane*
d1	Ship movement Pac. → Atl.; ship type 0	New, third (2-lift locks)
d2	Ship movement Atl. → Pac.; ship type 0	New, third (2-lift locks)
d3	Ship movement Pac. → Atl.; ship type VIII	New, third (2-lift locks)
d4	Ship movement Atl. → Pac.; ship type VIII	New, third (2-lift locks)
d5	Ship movement Pac. → Atl.; ship type VII	New, third (2-lift locks + wsb's)
d6	Ship movement Atl. → Pac.; ship type VII	New, third (2-lift locks + wsb's)
d7	Gatun Spillway; daily discharge = 5.10^6 m^3 Gatun Power Station; daily discharge = 5.10^6 m^3 Mirflaores Spillway (+cooling) ; daily discharge = 5.10^4 m^3	-
d8	Ship movement Pac. → Atl.; ship type VI	New, third (2-lift locks)
d9	Ship movement Atl. → Pac.; ship type VI	New, third (2-lift locks)
d10	Ship movement Pac. → Atl.; ship type V	New, third (2-lift locks)
d11	Ship movement Atl. → Pac.; ship type V	New, third (2-lift locks)
d12	Ship movement Pac. → Atl.; ship type IV	New, third (2-lift locks + wsb's)
d13	Ship movement Atl. → Pac.; ship type IV	New, third (2-lift locks + wsb's)
d14	Ship movement Pac. → Atl.; ship type III Ship movement Pac. → Atl.; ship type VIII Ship movement Pac. → Atl.; ship type VIII	West + East New, third (2-lift locks) New, third (2-lift locks + wsb)
d15	Ship movement Atl. → Pac.; ship type III Ship movement Atl. → Pac.; ship type VIII Ship movement Atl. → Pac.; ship type VIII	West + East New, third (2-lift locks) New, third (2-lift locks + wsb)
d16	Turn around Pacific side, N → S Turn around Pacific side, S → N Turn around Atlantic side, S → N Turn around Atlantic side, N → S	New, third (2-lift locks)
d17	Turn around Pacific side, N → S Turn around Pacific side, S → N Turn around Atlantic side, S → N Turn around Atlantic side, N → S	New, third (2-lift locks + wsb)

Table 6.1 Overview of Day Patterns used in test cases

Test cases were such designed that the functioning of in particular the new items could be checked. The above Day Patterns and next Coefficient Sets were used in the test runs:

Coefficient Set	*Up equalize*	*Up ship*	*Down equalize*	*Down ship*	*Up fill*	*Up empty*	*Down fill*	*Down empty*	*Exchange with lakes*	*Water releases*
c1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
c2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
c3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
c4	0.1	0.3	0.5	0.7	0.2	0.4	0.6	0..8	1.0	1.0
c5	0.5	0.2	0.5	0.2	0.5	1.0	0.5	1.0	1.0	1.0

Table 6.2 Overview of Coefficient Sets used in test cases

Test series A

A first series of tests was done with the salt concentration of all basins (including Pacific and Atlantic tailbays) set on 0. The purpose of these tests was to check the handling of water levels, water volumes, water displacement of new ship types and the set up of the water balance when a ship moves from ocean to ocean. The results of the water-balance computations have been checked by computations 'by hand'.

An overwiew of test cases of test series A is presented in Table 6.3.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
1	c1	d1	Jan 1 – Jan 31, 1970	scenario	single ship, S = 0
1-R	c1	d2	Jan 1 – Jan 31, 1970	scenario	single ship, S = 0
2A	c1	d3	Jan 1 – Jan 31, 1970	scenario	single ship, S = 285000
2A-R	c1	d4	Jan 1 – Jan 31, 1970	scenario	single ship, S = 285000
3A	c1	d5	Jan 1 – Jan 31, 1970	scenario	single ship, S = 260000
3A-R	c1	d6	Jan 1 – Jan 31, 1970	scenario	single ship, S = 260000

Table 6.3 Test cases series A: initial salt concentration is zero in all basins

Conclusions test series A

Water levels and water volumes, also those of the new basins in the simulation model, are well computed. Water transfer in the existing locks, new locks and wsb's caused by uplocking and downlocking ships is correct simulated and the water quantities fulfil the water balance.

Test series B

The set up of water balance and salt balance, the use of exchange coefficients, the time-dependent exchange of salt water between forebays and lakes, the proper functioning of spillways and the salt-water migration process from the lakes downwards has been checked in test series B. The initial salt concentration of Miraflores Lake and Gatun Lake was set on 30 ppt, the initial salt concentration of all other basins was set on 0.

An overwiew of test cases of test series B is presented in Table 6.4.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*

4	c2	d7	Jan 1 – Dec 31, 1970	day	water releases
5A	c3	d1	Jan 1 – Jan 5, 1970	scenario	single ship, S = 0
5A-R	c3	d2	Jan 1 – Jan 5, 1970	scenario	single ship, S = 0
5B	c3	d8	Jan 1 – Jan 5, 1970	scenario	single ship, S = 200000
5B-R	c3	d9	Jan 1 – Jan 5, 1970	scenario	single ship, S = 200000
6	c4	d10	Jan 1 – Jan 5, 1970	scenario	single ship, S = 145000
6-R	c4	d11	Jan 1 – Jan 5, 1970	scenario	single ship, S = 145000
7	c4	d12	Jan 1 – Jan 5, 1970	scenario	single ship, S = 120000
7-R	c4	d13	Jan 1 – Jan 5, 1970	scenario	single ship, S = 120000
8	c5	d14	Jan 1 – Jan 5, 1970	scenario	several ships / all lanes
8-R	c5	d15	Jan 1 – Jan 5, 1970	scenario	several ships / all lanes

Table 6.4 Test cases series B: initial salt concentration of Gatun Lake and Miraflores Lake = 30 ppt, initial salt concentration of all other basins = 0

Conclusion test series B

The water balance and salt balance are well computed: salt water migrates properly from the lakes to all lower basins and to wsb's, the time-dependent exchange of salt water between forebays / tailbays and lakes is correct, the loss of salt water through water releases at Gatun Dam and Miraflores is well computed.

Test series C

In this third series of test cases the salt concentration of the tailbays at the Pacific and Atlantic side was set on 30 ppt. The aim of the tests was to check the salt-water intrusion from the seas into the lakes, and to check the turn around scenarios.
An overwiew of test cases of test series C is presented in Table 6.5.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
9	c5	d3	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
10-R	c5	d6	Jan 1 – Jan 5, 1970	scenario	single ship, S = 260000
11A	c4	d16	Jan 1 – Jan 5, 1970	scenario	turn arounds new lane (2-lift locks)
11B	c4	d17	Jan 1 – Jan 5, 1970	scenario	turn arounds new lane (2-lift locks + wsb)

Table 6.5 Test cases series C: initial salt concentration of Pacific and Atlantic tailbays = 30 ppt, initial salt concentration of all other basins = 0

Conclusion test series C

The water balance and salt balance are well computed: salt water migrates properly from the tailbays in the sea entrances to all higher basins and to wsb's, the time-dependent exchange of salt water between forebays / tailbays and lakes is correct. Turn around scenarios are correctly executed.

As a last test the validation case for the existing situation (Case VAL1, see Report A) has been run as Case A-1 with the extended simulation model. The extended model produced fully identical results, see Figures A-1, 1 and A-1, 2.

7 Salt water intrusion analysis future situation

In this section we present the results of the salt-water intrusion analysis for the future situation with a new, third shipping lane. Two-lift Post-Panamax locks are built at both ends of the new lane. The locks are provided with water saving basins (wsb's, see also Section 2). In the analysis we make a distinction between the situation that wsb's are not in use and the situation that the wsb's are used to prevent the loss of water from Gatun Lake. A comparison with the present salt-water intrusion through the existing locks concludes the analysis.
Starting point for the analysis is that the water levels in Miraflores Lake and Gatun Lake vary throughout the year as in the existing situation. In the baseline scenario the water releases (through Gatun Spillway, Gatun Power Station, Miraflores Spillway, Miraflores Cooling Water Offtake) remain as they are in the existing situation (which means that additional water is supplied to Gatun Lake to compensate for the extra losses via the new locks). In the second scenario the water releases at Gatun Dam are reduced with the water losses caused by shipping in the new lane. In the case that these water losses are greater than the water releases (this will in particular occur in the dry season) we assume that additional water supplies are available to replenish the surplus losses. The ship transit prospects for the next 50 years as given by ACP are used.

7.1 Data used in numerical simulations

The next data is applied in the numerical simulations:

- Dimensions of locks, forebays, tailbays, water saving basins: the dimensions presented in Section 3.7 are selected.
- Water levels and salt concentrations of seaside tailbays: values presented in Section 3.9 are selected.
- Water levels and corresponding water volumes, water releases of Miraflores Lake and Gatun Lake: values presented in Section 3.8 are selected.
- Initialization data: see Section 3.10
- Exchange coefficients: see Chapter 5.

7.2 Set up of cases for simulation of the future situation

We assume that the new lane will come in operation at January 1, 2011. The present salt concentrations in Gatun Lake, Miraflores Lake and the locks on the existing shipping lanes are selected as initial salt concentrations. These salt concentrations have been obtained through numerical simulation of the salt water intrusion during the preceding year 2010. The initial salt concentrations in the new locks and wsb's are set to the values of the existing locks. This is not conform the real situation, but as can be seen from the computational results the salinity values in the new locks and wsb's grow fast to an equilibrium value.

The salt intrusion in the future situation is analysed for a period of 1 month, 1 year, 5, 10, 20 and 50 years after opening of the third lane. Various cases have been set up to simulate the salt intrusion during these periods. Day patterns which are applied in the various cases, are such defined that they reflect the development of the ship traffic intensities in the next 50 years. In next table the daily number of transiting ships and the type of ships are presented for the various consecutive time periods. Panamax vessels are represented by ship type III, regular ships by ship types I and II, Panamax-Plus vessels by ship type IV, Post-Panamax vessels by ship type VII (draught 14 m, during first 5 years after opening of the new lane) and ship type VIII (draught 15.2 m).

Period	*Jan 1, 2011 – Jan 31, 2011*	*Febr 1, 2011 – June 30, 2011*	*July 1, 2011 – Dec 31, 2011*	*Jan 1, 2012 – Dec 31, 2012*	*Jan 1, 2013 – Dec 31, 2015*	*Jan 1, 2016 – Dec 31, 2020*	*Jan 1, 2021 – Dec 31, 2025*	*Jan 1, 2026 – Dec 31, 2030*	*Jan 1, 2031 – Dec 31, 2040*	*Jan 1, 2041 – Dec 31, 2050*	*Jan 1, 2051 – Dec 31, 2060*
Vessel type	*Number of ships*										
Existing shipping lane West											
Type I	8	8	8	8	8	8	8	8	8	8	8
Type II	4	4	4	4	4	4	4	4	4	4	4
Type III	6	6	6	6	6	6	6	6	6	6	6
Total	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Existing shipping lane East											
Type I	8	8	8	8	8	8	8	8	8	8	8
Type II	4	4	4	4	4	4	4	4	4	4	4
Type III	6	6	6	6	6	6	6	6	6	6	6
Total	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Future third shipping lane (2-lift locks)											
Type IV	2	3	4	4	4	4	4	4	4	5	5
Type VII	0	0	1	2	0	0	0	0	0	0	0
Type VIII	0	0	0	0	2	3	4	5	7	9	10
Total	**2**	**3**	**5**	**6**	**6**	7	**8**	**9**	**11**	**14**	**15**
Simulations											
Period after opening of new lane	**1 month**	0.5 year	**1 year**	2 years	**5 years**	**10 years**	15 years	**20 years**	30 years	40 years	**50 years**

Table 7.1 Ship transits in simulation model in existing and new shipping lanes

In the set up of cases a distinction is made between 2-lift locks with and without wsb's and present water releases, and 2-lift locks with and without wsb's and reduced water releases from Gatun Lake, see Section 3.8 (water releases from Miraflores Lake remain as in the existing situation). The various cases are numbered as shown in Table 7.2.

In the baseline scenario we assume that all extra water losses caused by lock operation in the new shipping lane are compensated by extra water supplies to Gatun Lake, but water spills at Gatun Dam are not reduced. When the wsb's of the two-lift locks in the new lane are in use (Case C1) the extra water supply amounts to 4.10^5 m^3 water per transiting ship (leading to a water supply in year 50 of 6.10^6 m^3 per day). When the wsb's are not applied (Case C2) the extra water supply to Gatun Lake amounts to 8.10^5 m^3 water per transiting ship (leading to a water supply in year 50 of 12.10^6 m^3 per day).
In the second scenario we assume that the water releases at Gatun Dam are reduced with the water losses caused by the new locks. Consequently, a lesser quantity of fresh water has to be supplied to Gatun Lake. In the dry season, however, the spilled quantities are small or nil and extra water supplies are still needed to compensate for the water losses of the new locks (see also Tables 3.18 and 3.19). When wsb's are used (Case C3) the water loss is 50% smaller than when they are out of use (case C4).
For reasons of comparison we have also simulated the salt water intrusion in the period 2011 – 2020 when no new shipping lane is realised. This case is indicated with A-10. The results for year 10 are in fact also valid for year 1, 5, 20 and 50, since these values are stable, equilibrium values for the given ship traffic intensity in the existing locks.

Simulation time	Existing Situation	Future Situation 2-lift locks **with** wsb's (baseline)	Future Situation 2-lift locks **without** wsb's	Future Situation 2-lift locks **with** wsb's and reduced water releases GL	Future Situation 2-lift locks **without** wsb's and reduced water releases GL
1 month		C1-1m	C2-1m		
1 year		C1-1	C2-1	C3-1	C4-1
5 years		C1-5	C2-5		
10 years	A-10	C1-10	C2-10	C3-10	C4-10
20 years		C1-20	C2-20	C3-20	C4-20
50 years		C1-50	C2-50	C3-50	C4-50

Table 7.2 **Overview of cases**

For the new shipping lane with alternative 3-lift locks or 1-lift locks we reserve the letters B and D respectively for designation of the cases.

7.3 Results of simulations and analysis

The computed salt concentrations (ppt) of Miraflores Lake and Gatun Lake in the period year 2016 – year 2020 (ending 10 years after opening of new lane) and the period year 2051 – year 2060 (ending 50 years after opening) are shown in Figures C1-10, 1 through C4-50, 2. The results for the existing situation (no new lane) for the period year 2011 – year 2020 are shown in Figures A-10, 1 and A-10, 2. As can be seen the salt concentrations of Miraflores Lake and Gatun Lake fluctuate as a function of wet and dry season; the salt concentration levels stabilize within a period of about 1- 2 years after a change in ship traffic intensity.

The maximum and minimum values of the salt concentration of Miraflores Lake and Gatun Lake in the last year of the considered period are presented in Table 7.3.

Case	*Considered year*	*Salt conc. (ppt) Miraflores Lake*		*Salt conc. (ppt) Gatun Lake*	
		minimum	*maximum*	*minimum*	*maximum*
A-10	10	0.64	1.42	0.010	0.027
C1-1month	-	0.63	0.99	0.009	0.017
C1-1	1	0.63	1.10	0.009	0.09
C1-5	5	0.66	1.67	0.08	0.24
C1-10	10	0.70	1.66	0.11	0.33
C1-20	20	0.75	1.85	0.17	0.47
C1-50	50	0.82	2.30	0.38	1.03
C2-1month	-	0.63	0.99	0.009	0.013
C2-1	1	0.63	1.07	0.009	0.05
C2-5	5	0.65	1.55	0.04	0.11
C2-10	10	0.67	1.53	0.06	0.16
C2-20	20	0.70	1.69	0.10	0.26
C2-50	50	0.72	1.94	0.21	0.57
C3-1	1	0.63	1.56	0.009	0.18
C3-10	10	0.74	1.72	0.18	0.43
C3-20	20	0.83	1.98	0.31	0.66
C3-50	50	1.17	2.83	1.00	1.69
C4-1	1	0.63	1.50	0.009	0.09
C4-10	10	0.72	1.60	0.15	0.27
C4-20	20	0.83	1.86	0.31	0.46
C4-50	50	1.15	2.47	0.98	1.10

Table 7.3 Maximum and minimum values of salt concentration of Miraflores Lake and Gatun Lake

The maximum and minimum values are also shown in Figures 7.1 (Miraflores Lake) and 7.2 (Gatun Lake). From Figure 7.1 it appears that the salt concentration of Miraflores Lake increases slowly compared to the present situation (in all four cases C1-C4). Case C4 is most unfavourable with an increase up to a factor 2 in year 50. Though Miraflores Lake is by-passed by the new shipping lane, the new lane with Post-Panamax Locks has still an impact on the salinity of Miraflores Lake because extra salt water is spilled from Gatun Lake through Pedro Miguel locks into Miraflores Lake.
The salt concentration of Gatun Lake raises considerably: the salt concentration increases from the present very low, negligible salinity level to a salinity level in year 50 that is above the fresh water limit (a salinity level of 0.45 ppt can be regarded as 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).

It appears that Case C2 (no wsb's, no reduction of water releases at Gatun Dam) is most favourable in view of salt-water intrusion. This is caused by the large fresh-water supply to Gatun Lake. When wsb's are in operation (Case C1) a 50% smaller fresh-water supply is required and we see that the salt concentration levels increase. The salt concentration levels increase further when the water releases at Gatun Dam are reduced (Cases C3 and C4).

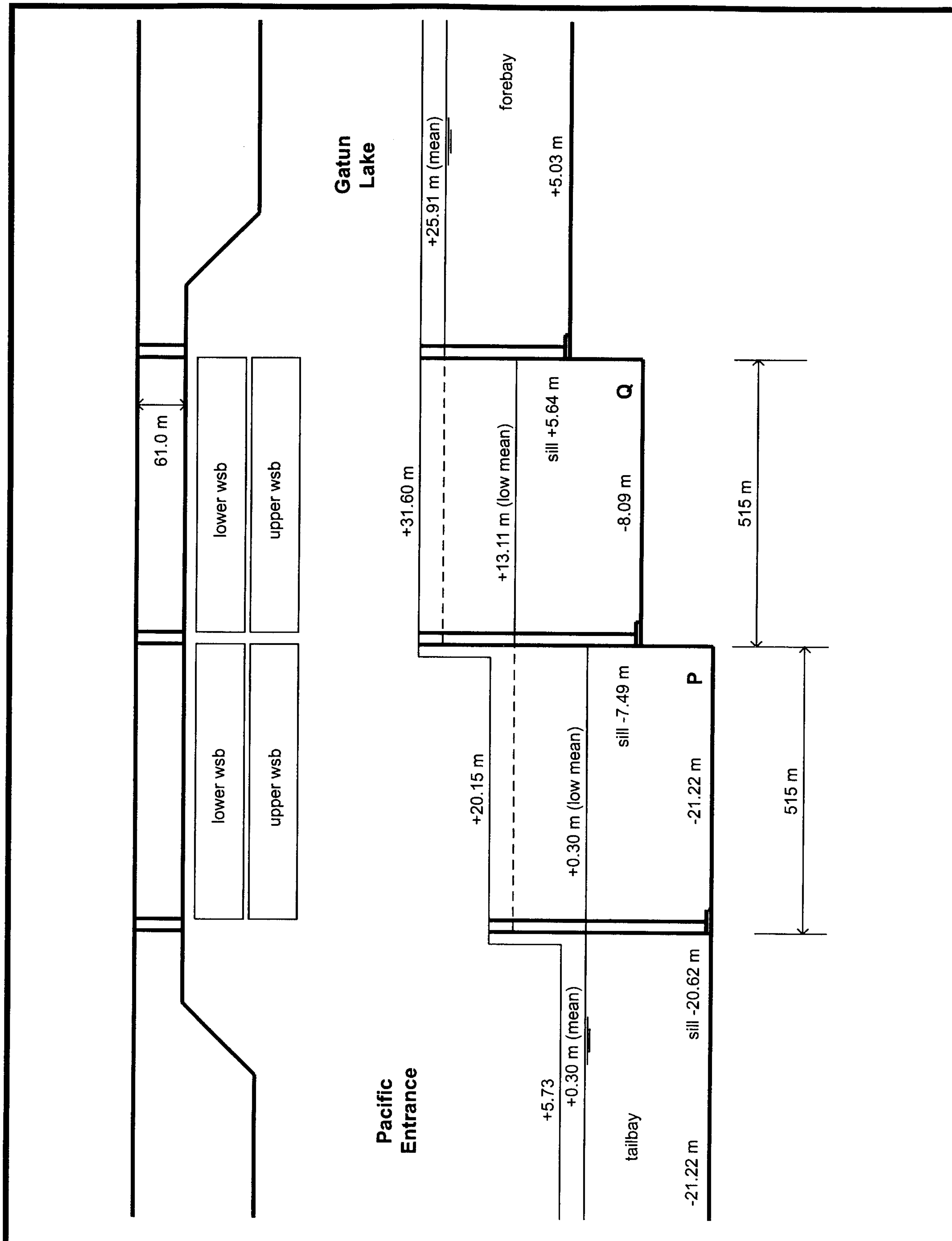
It should be noted that the computed concentration values are volume-averaged values, which means that local salt concentration values may be higher.

7.4 Sensitivity analysis

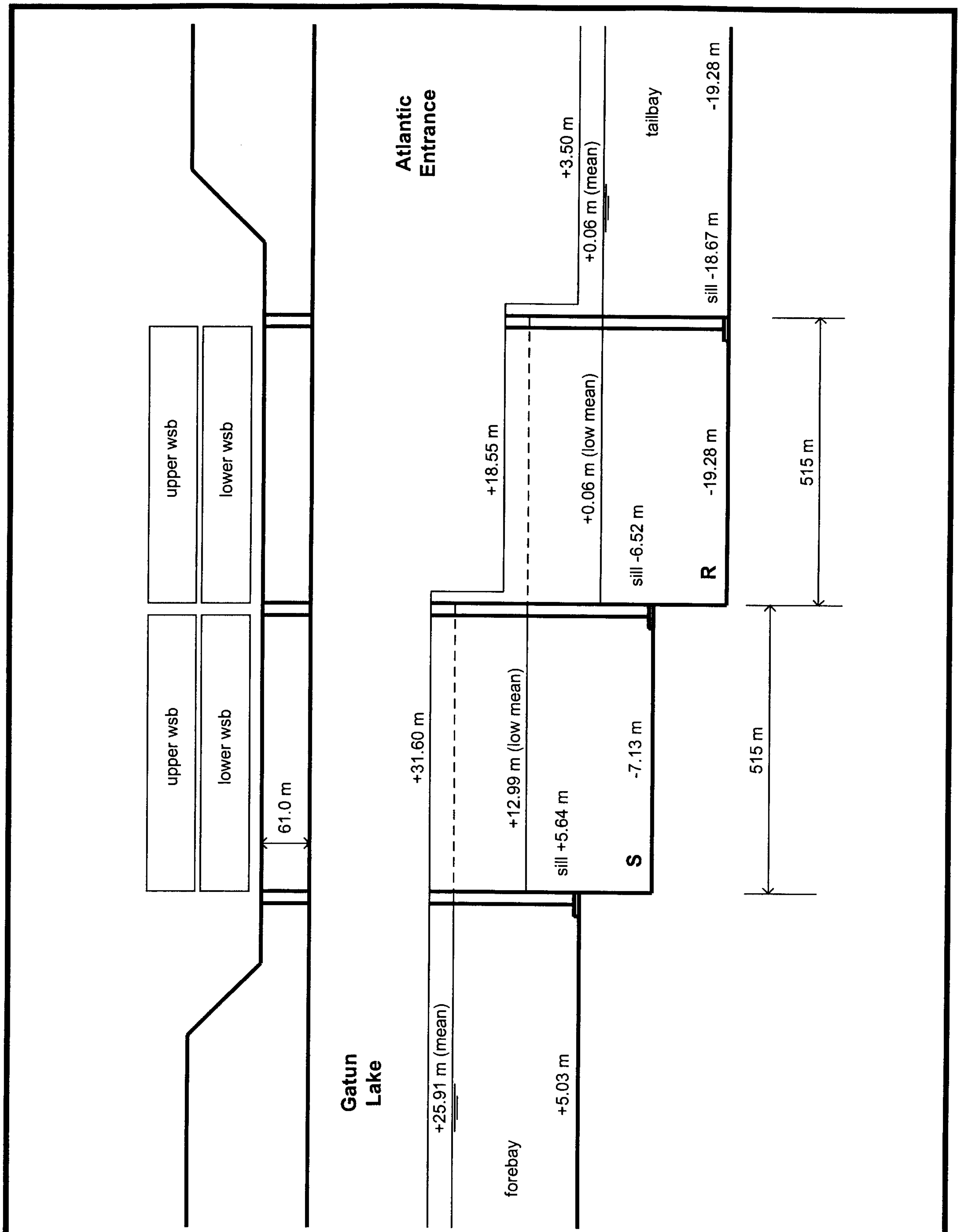
In a sensitivity analysis we have studied the effects of a variation of exchange coefficients for the two-lift locks in the new shipping lane. Most important coefficients are those which determine the exchange of salt water in step II of the uplockage and downlockage process (ship movements between tailbay and lower lock, lower lock and upper lock, upper lock and forebay). These coefficients have been varied in cases Sens1 and Sens2. The exchange coefficients which determine the salt water transfer in step I of the uplockage and downlockage process (equalize water levels between tailbay and lower lock, lower lock and upper lock, upper lock and forebay) have been varied in Sens3 and Sens4. For the values of exchange coefficients see Sections 5.1 and 5.2. The exchange coefficients of the existing locks have been kept constant (they are such selected that the salinity levels of Miraflores Lake and Gatun Lake in the present situation are correct predicted, see also Report A).

The results of the sensitivity analysis are shown in Figure 7.3 (Miraflores Lake) and Figure 7.4 (Gatun Lake). These figures present the salt concentration of the lakes for the base exchange coefficients and for variations of the exchange coefficients. The figures demontrate that the salt concentration of the lakes varies with the exchange coefficients, but this variation is relatively small compared to the effects of the two-lift locks on the salinity of, in particular, Gatun Lake. The tendency of a higher salinity level of Gatun Lake in the case of two-lift locks (with or without wsb's) is therefore reliable.

Figures



ASSUMED DESIGN OF 2-LIFT POST-PANAMAX LOCKS FOR PACIFIC SIDE, SHOWN SCHEMATICALLY		
WL | DELFT HYDRAULICS	Q 3039	Fig. 2.1

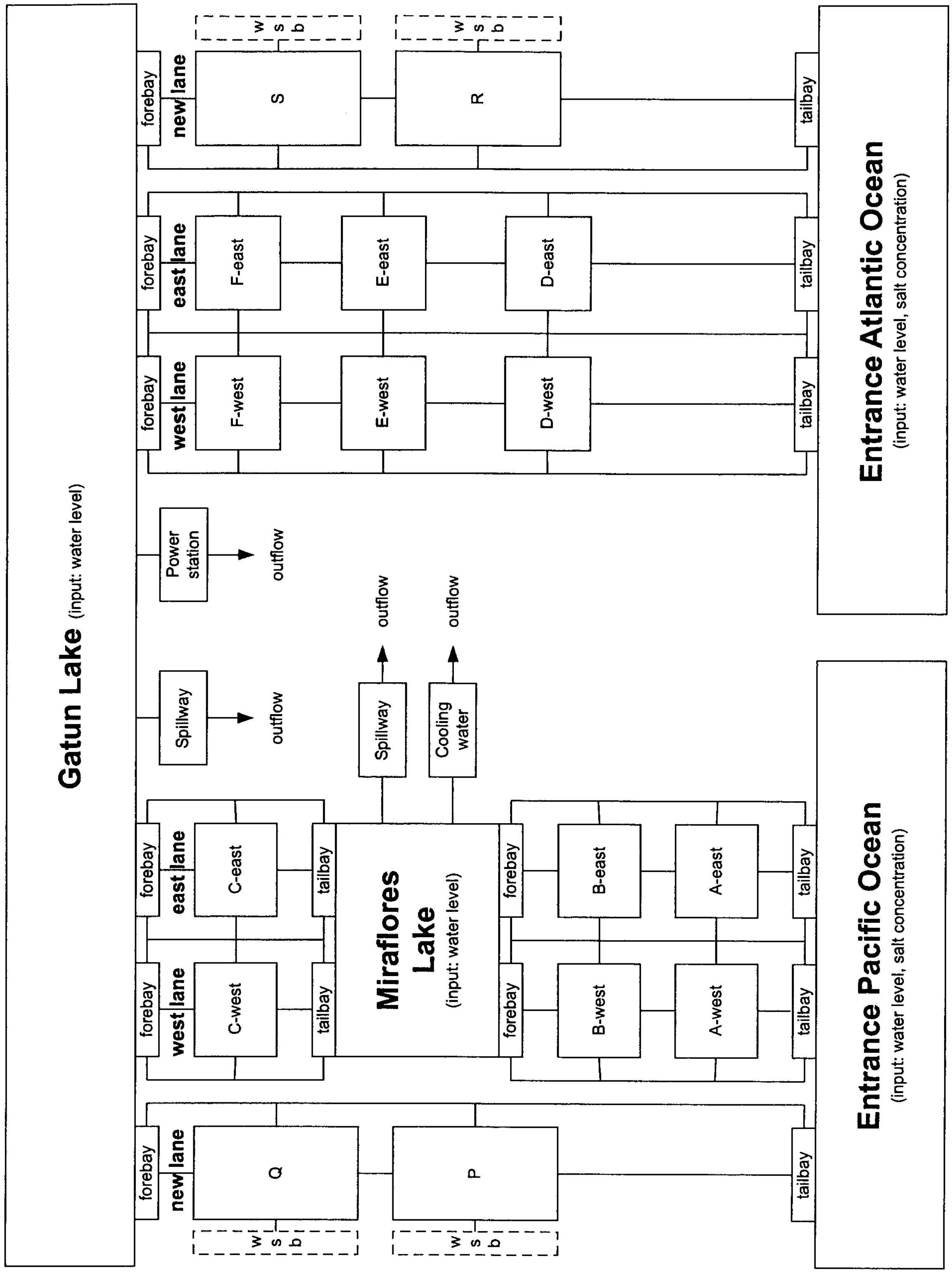


DESIGN OF 2-LIFT POST-PANAMAX LOCKS OF USACE FOR ATLANTIC SIDE, SHOWN SCHEMATICALLY

WL | DELFT HYDRAULICS

Q 3039

Fig. 2.2

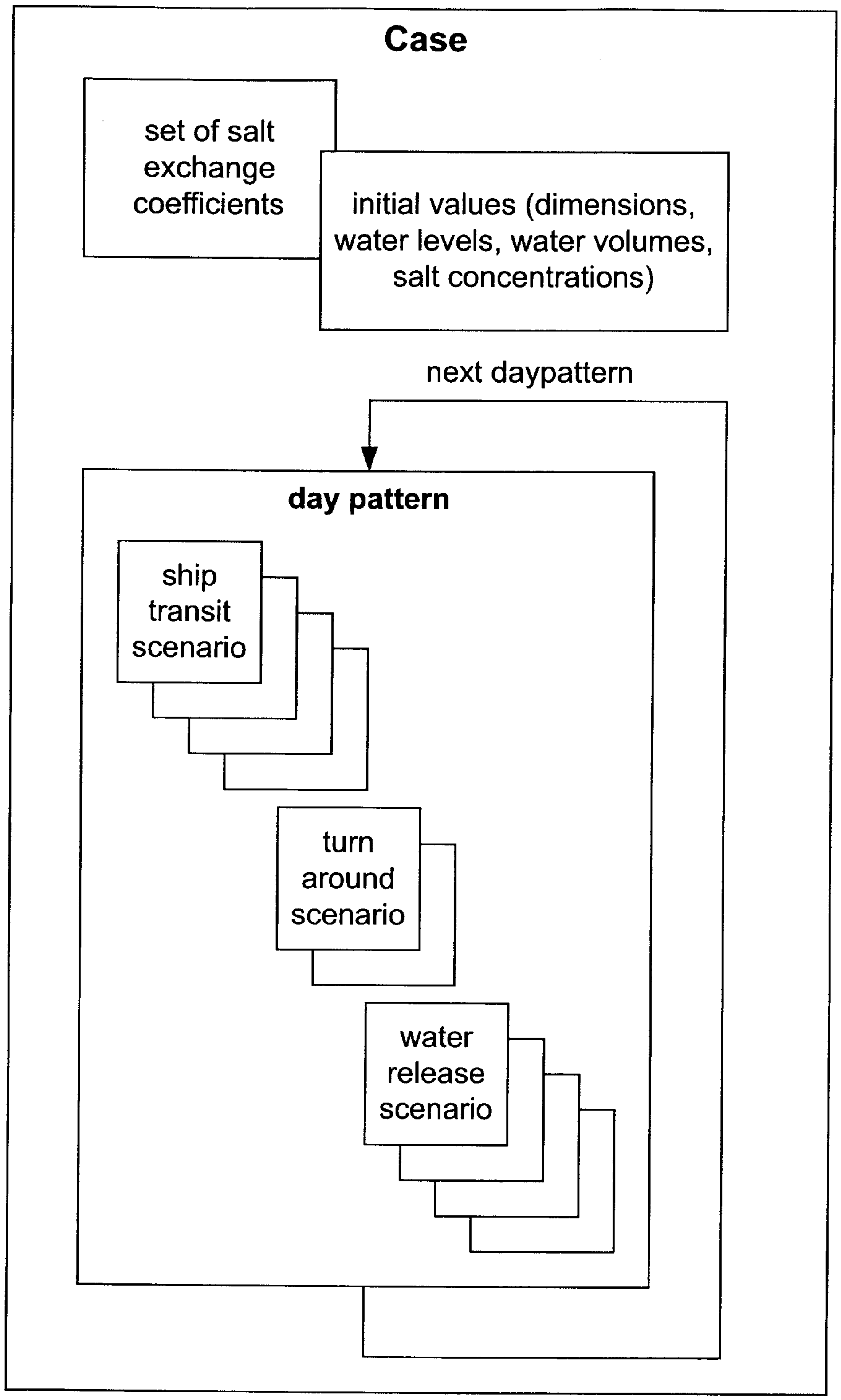


SIMULATION MODEL WITH NEW LANE AND 2-LIFT LOCKS.
NODES AND HYDRAULIC CONNECTIONS

WL | DELFT HYDRAULICS

Q 3039

Fig. 3 .1

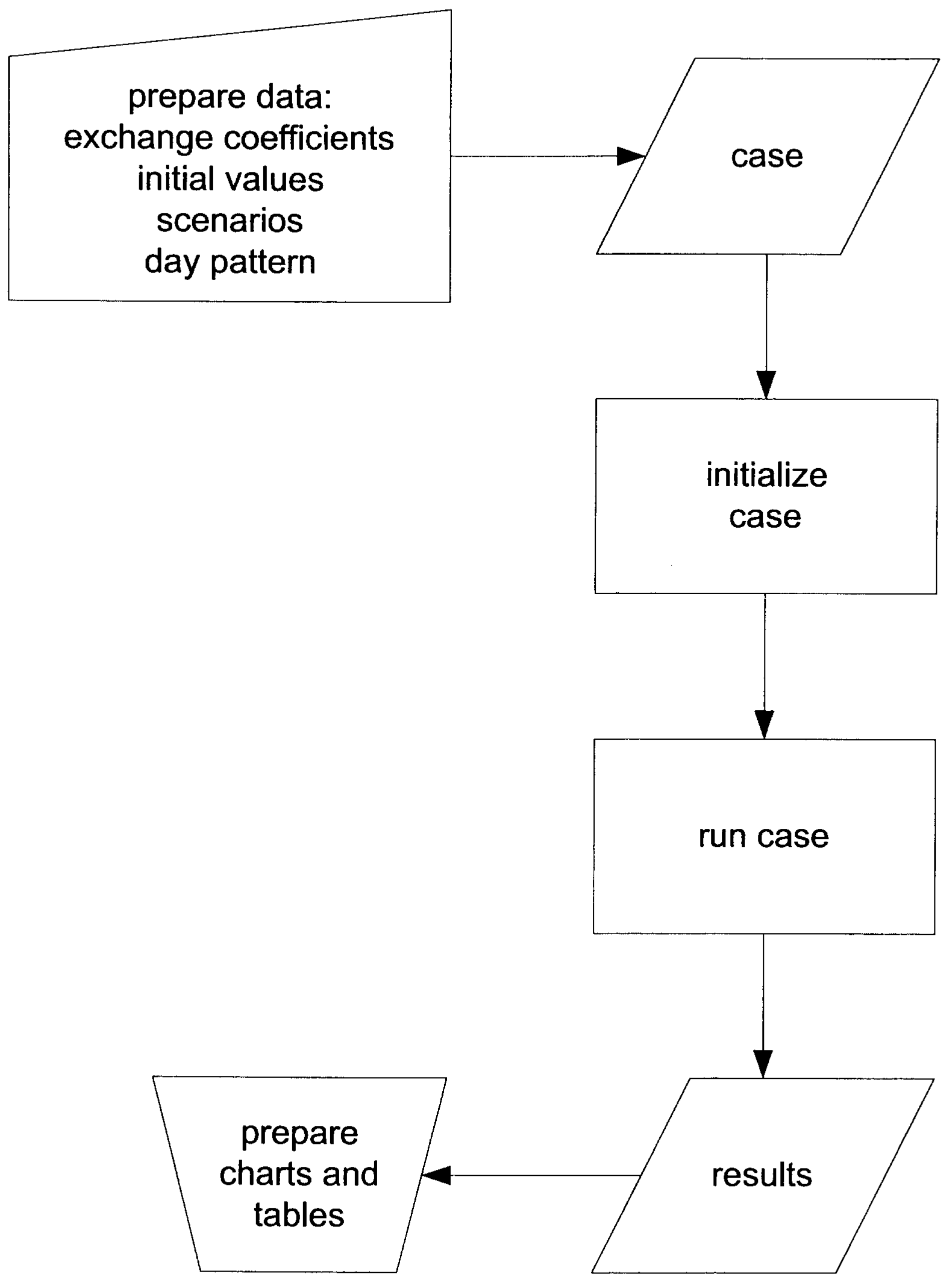


SIMULATION MODEL
COMPOSITION OF CASE

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.2

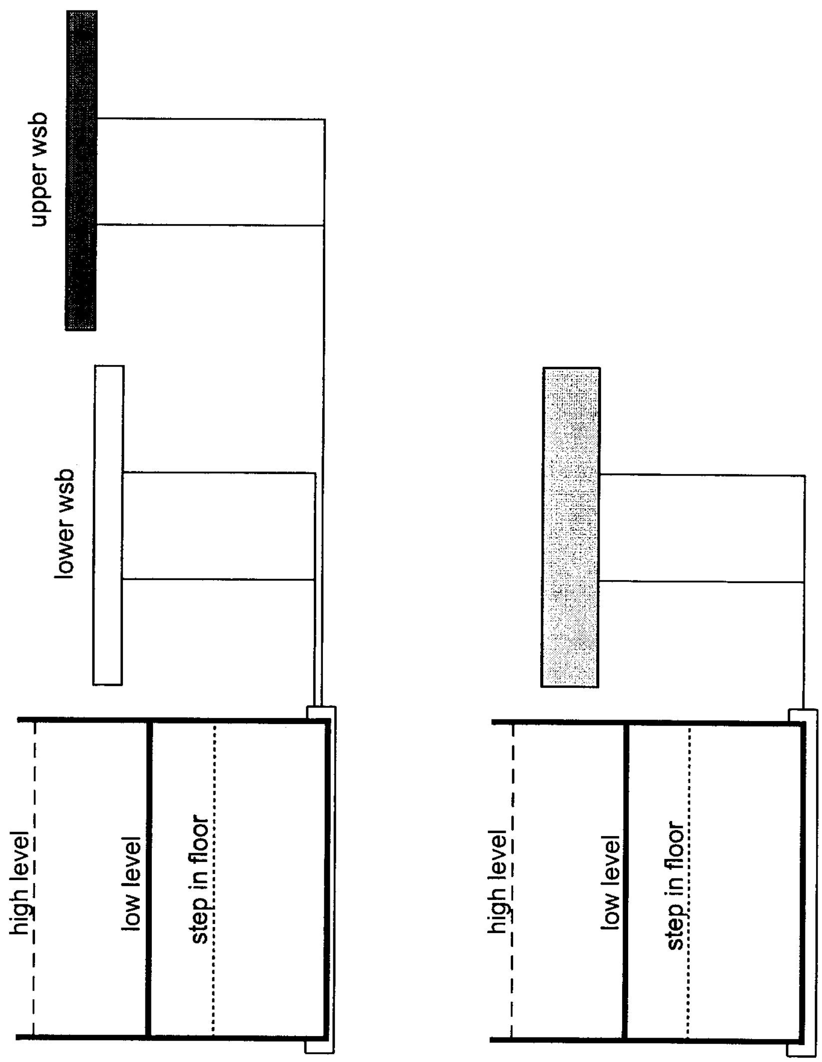


SIMULATION MODEL
FLOW CHART

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.3



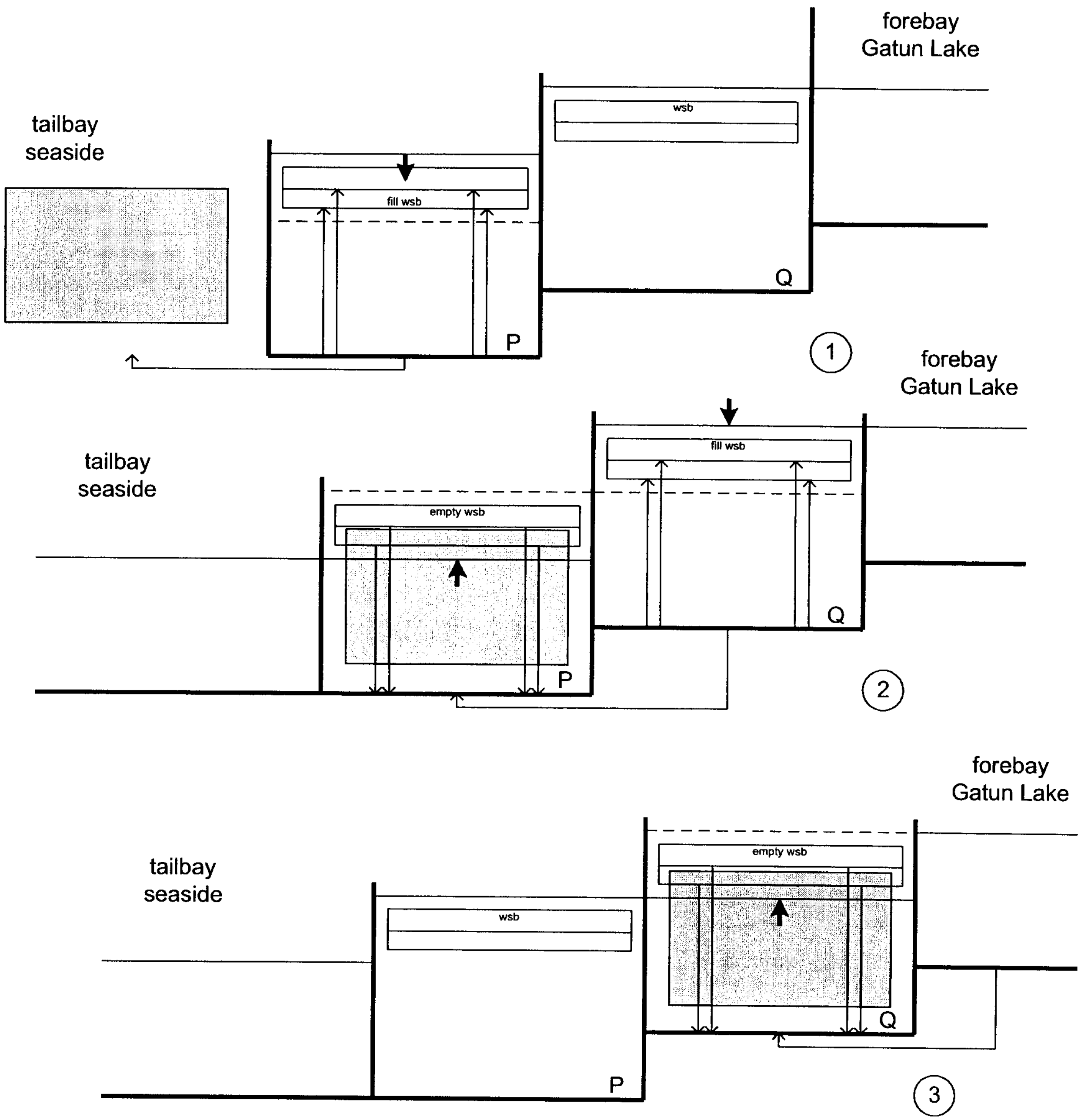
REPRESENTATION OF LOCK WITH 2 WSB'S
BY LOCK WITH SINGLE WSB

2-lift locks

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.4



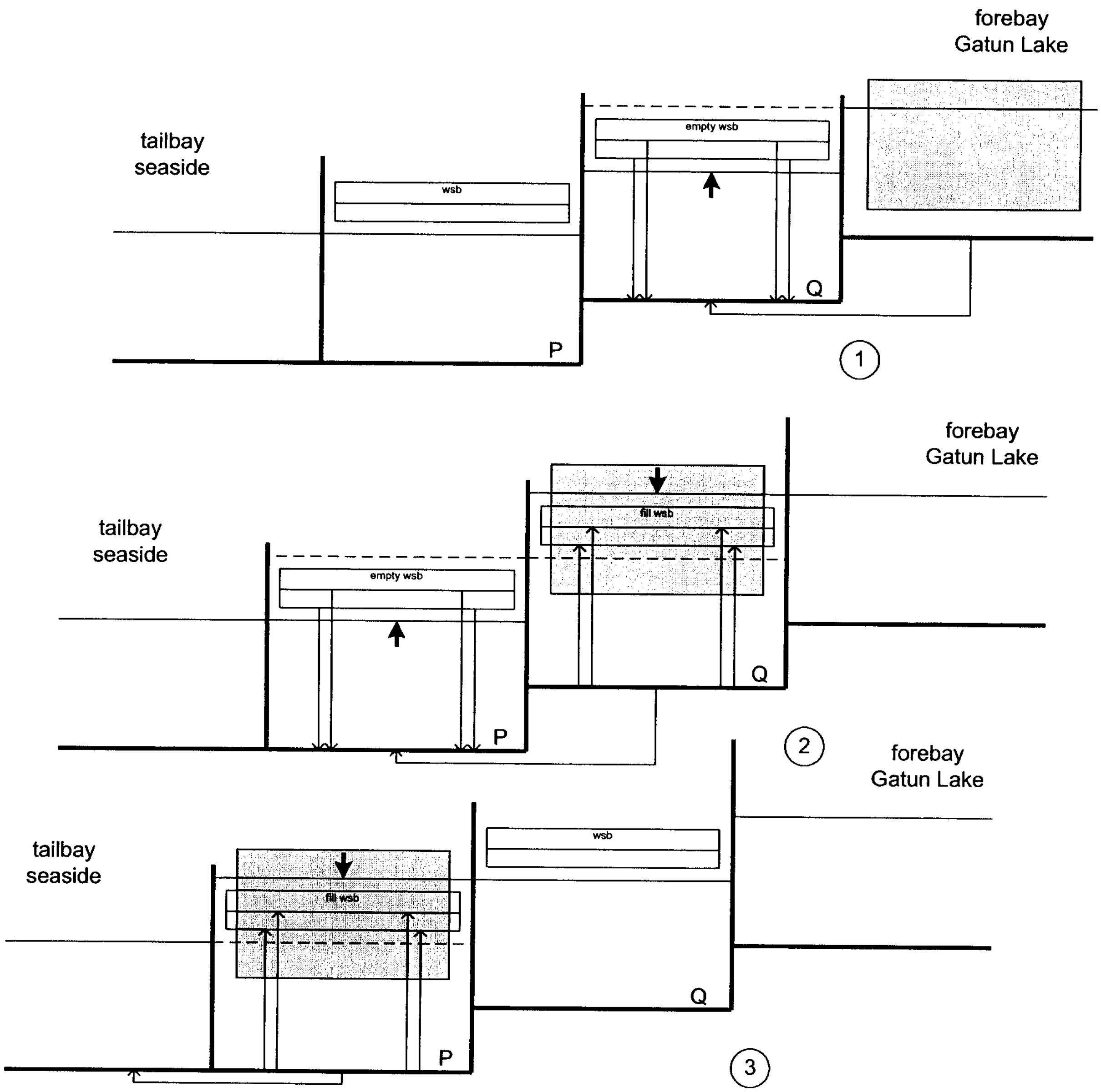
UPLOCKAGE
FILLING AND EMPTYING OF WSB'S IN STEP I

2-lift locks

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.5



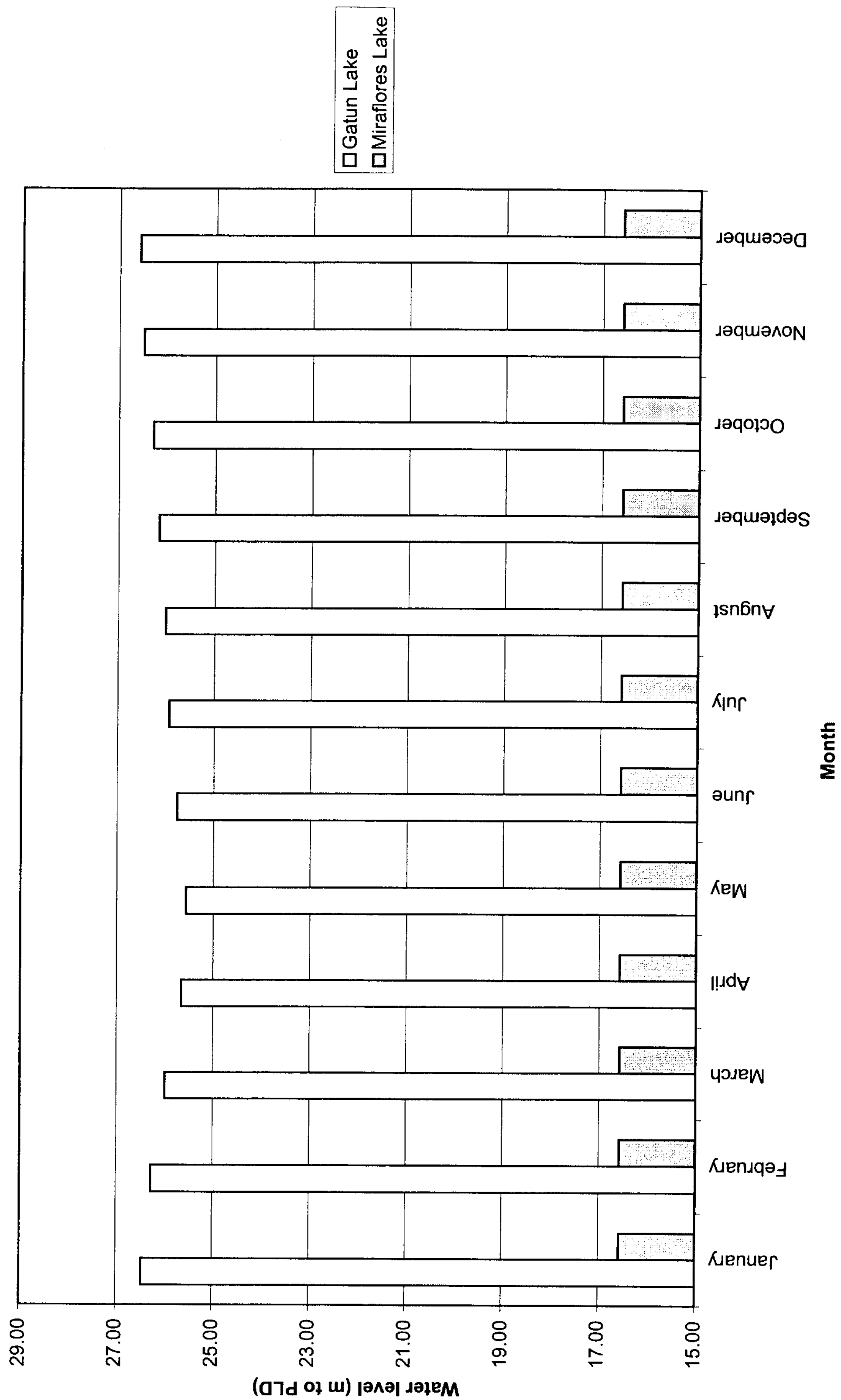
DOWNLOCKAGE
FILLING AND EMPTYING OF WSB'S IN STEP I

2-lift locks

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.6

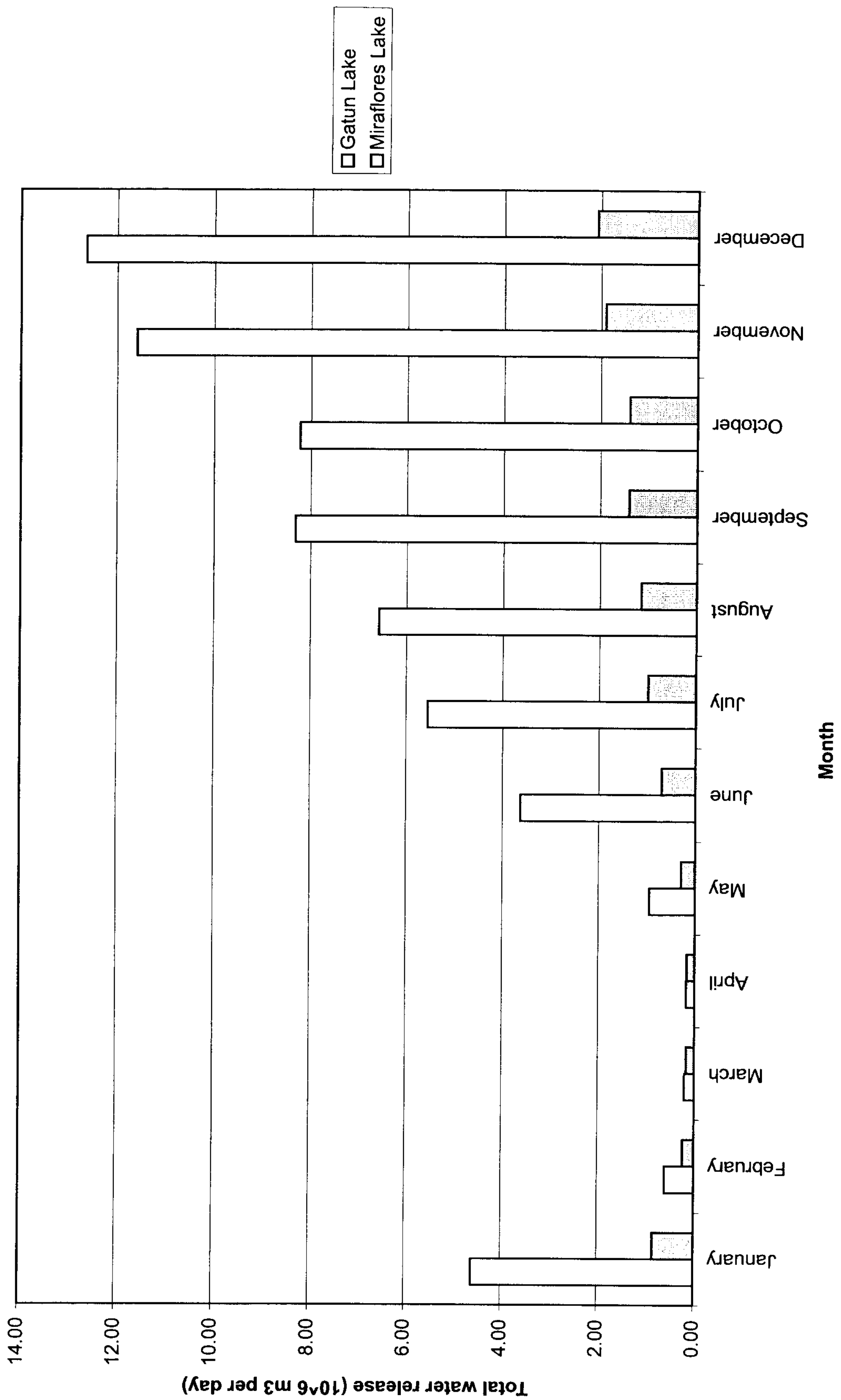


GATUN LAKE AND MIRAFLORES LAKE
REPRESENTATIVE WATER LEVELS

WL | DELFT HYDRAULICS

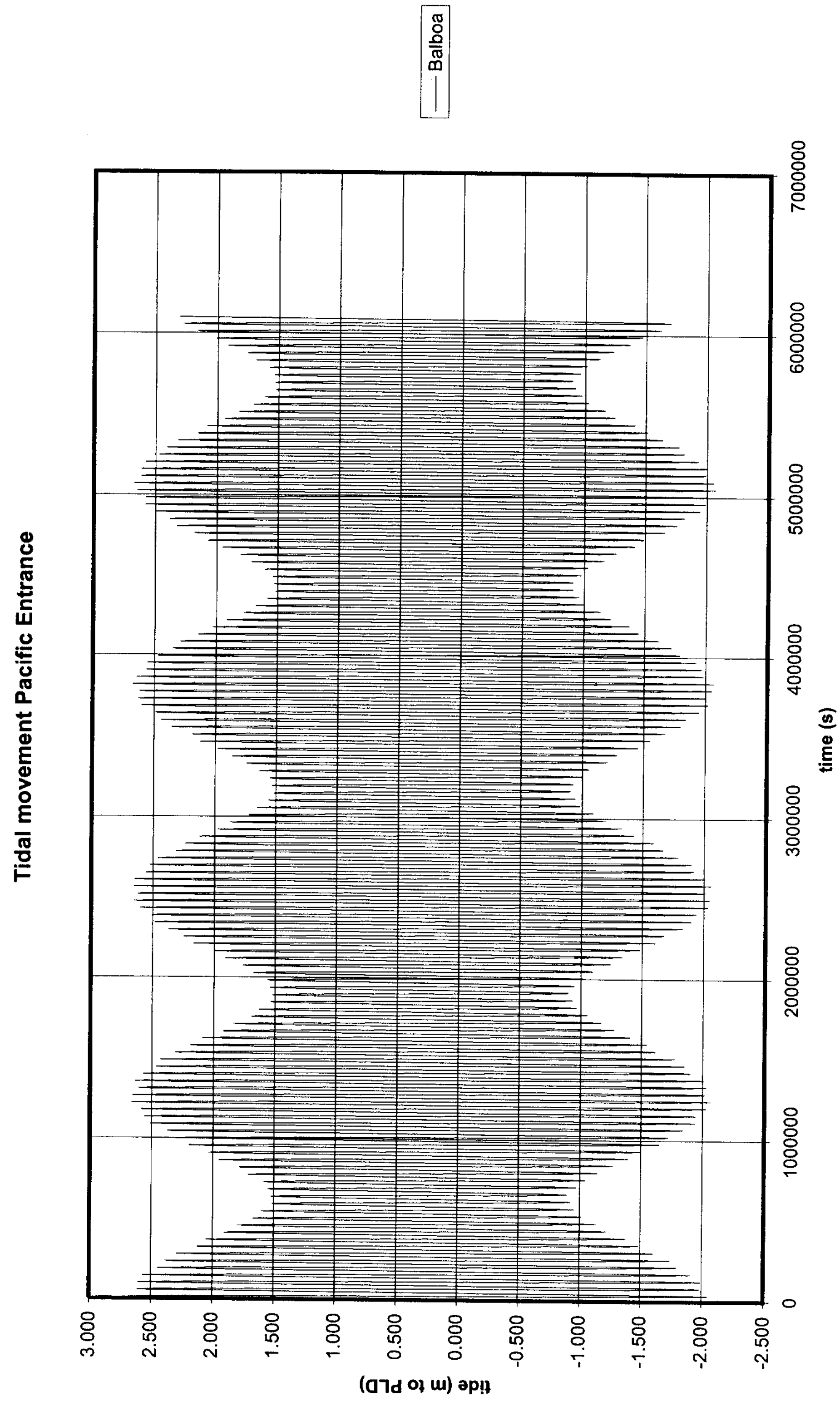
Q 3039

Fig. 3.7



GATUN LAKE AND MIRAFLORES LAKE
WATER RELEASES (BASELINE SCENARIO)

WL | DELFT HYDRAULICS	Q 3039	Fig. 3.8

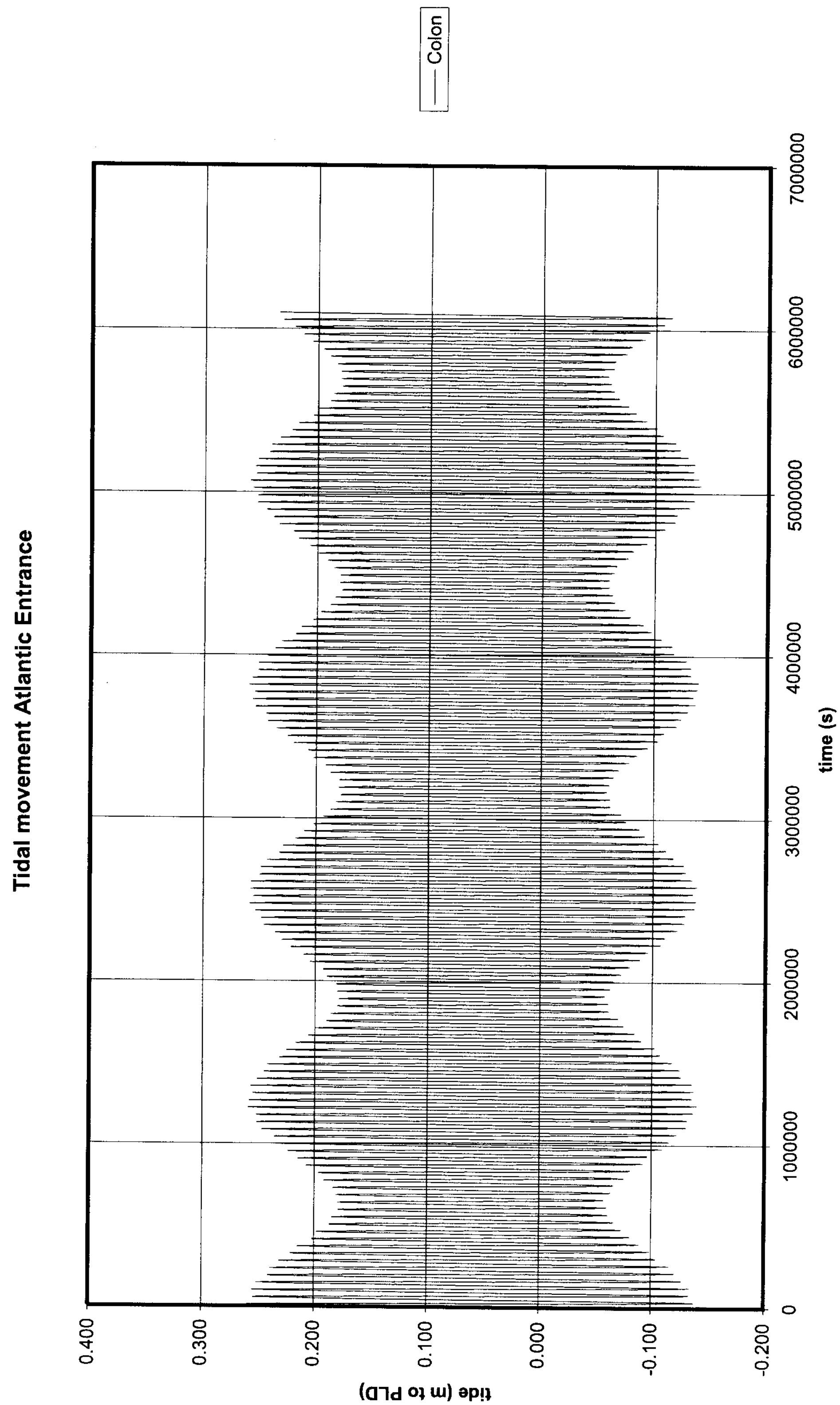


TAILBAYS PACIFIC SIDE
PREDICTION OF TIDAL MOVEMENT

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.9

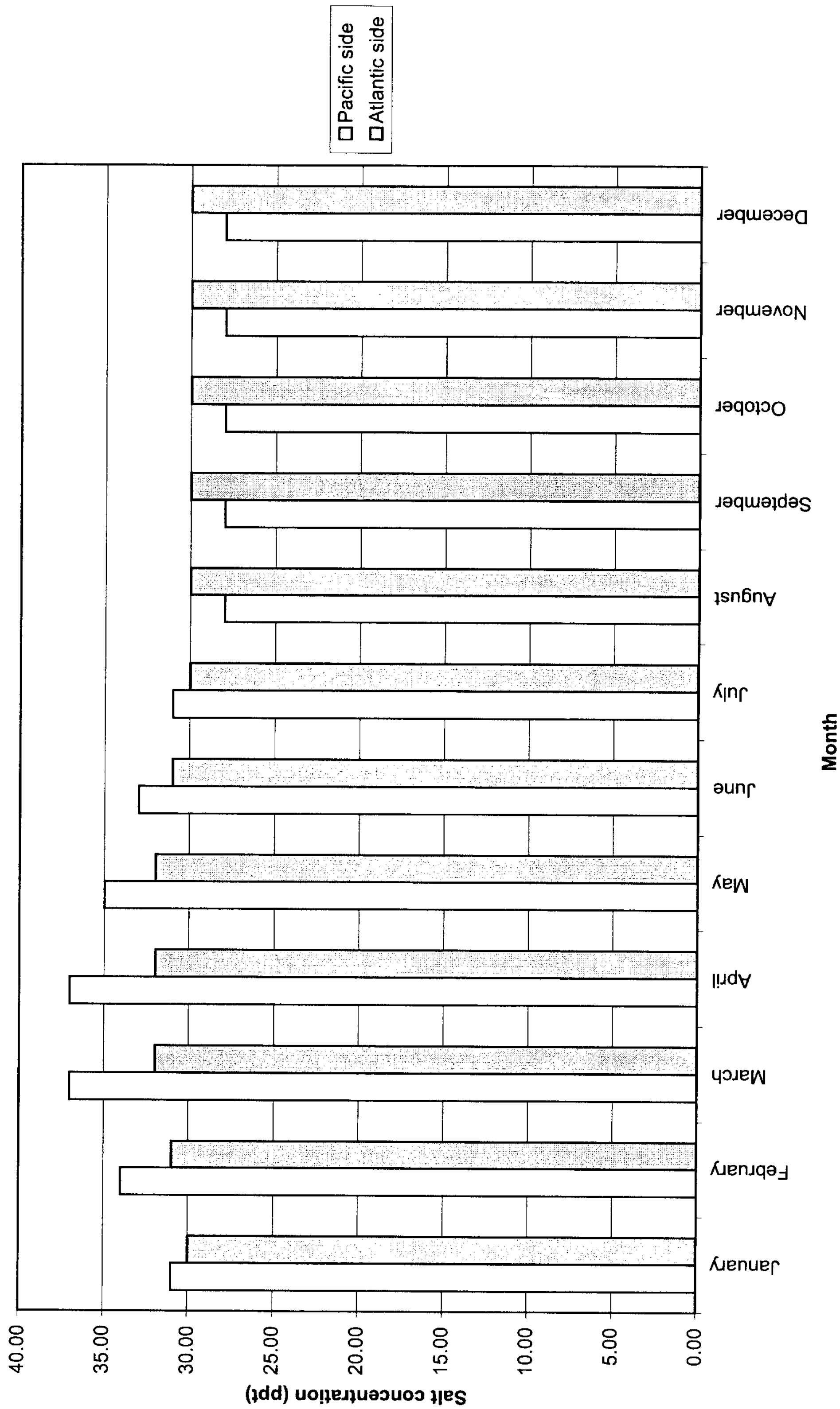


TAILBAYS ATLANTIC SIDE
PREDICTION OF TIDAL MOVEMENT

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.10

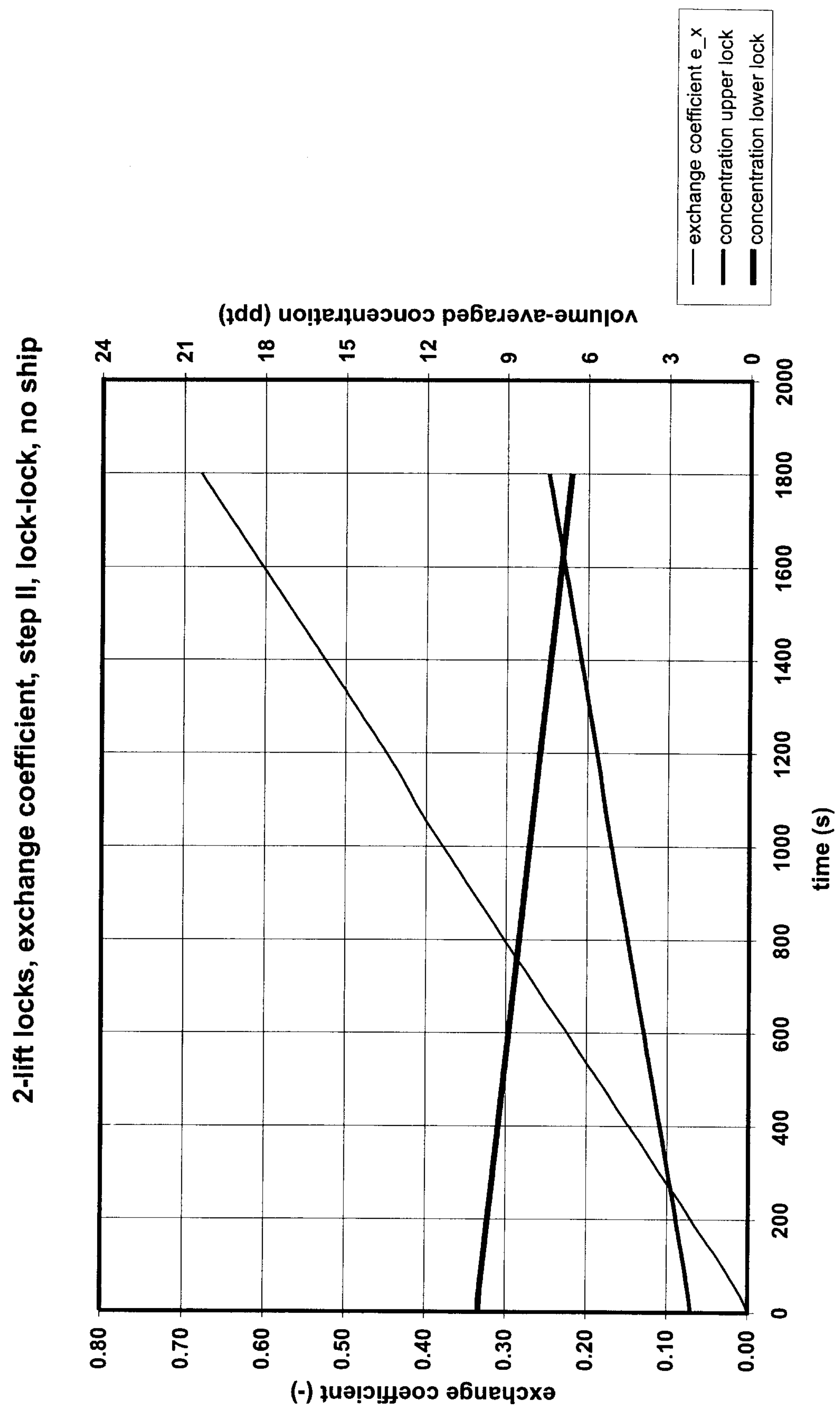


TEMPERATURE-COMPENSATED SALT CONCENTRATION OF PACIFIC AND ATLANTIC ENTRANCES

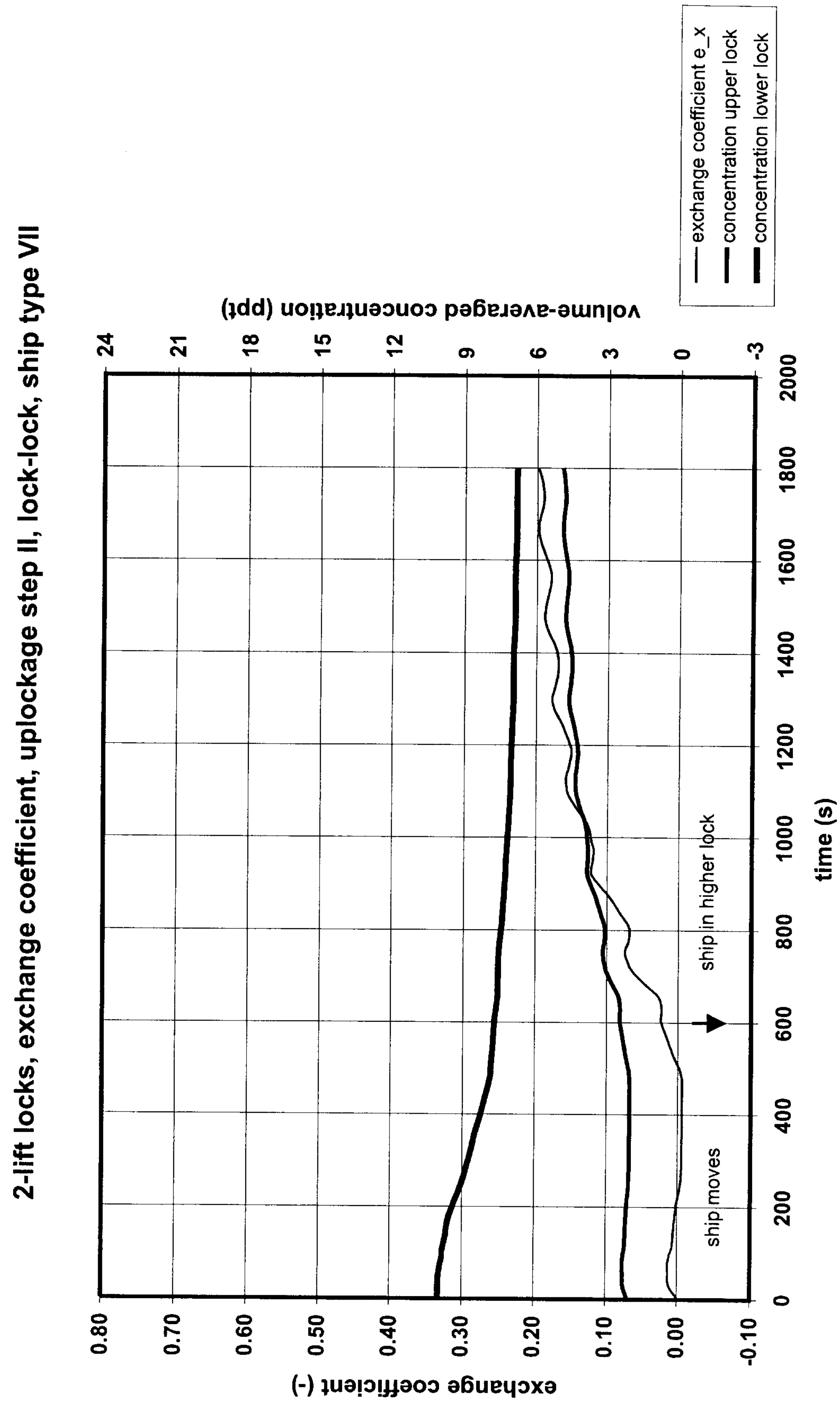
WL | DELFT HYDRAULICS

Q 3039

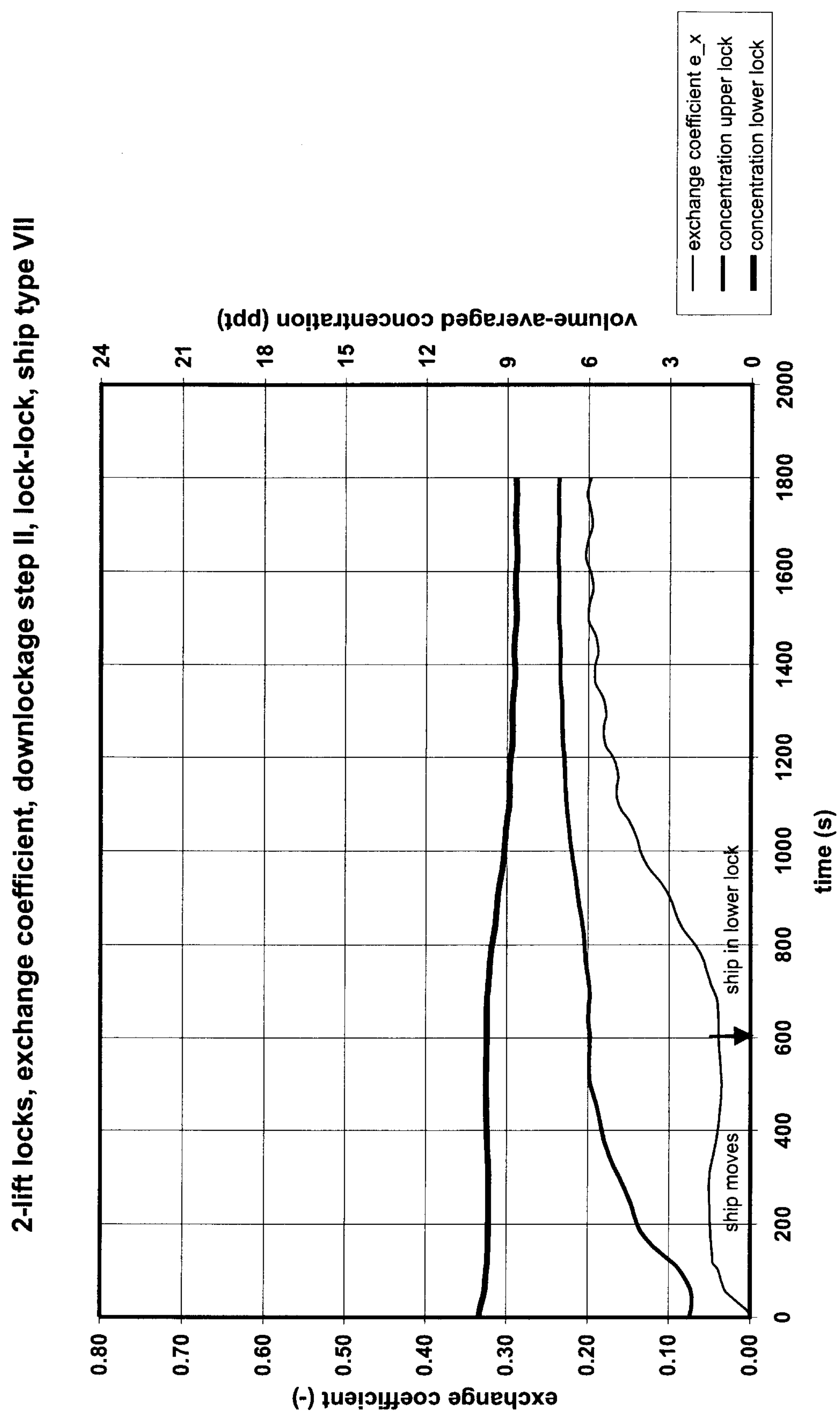
Fig. 3.11



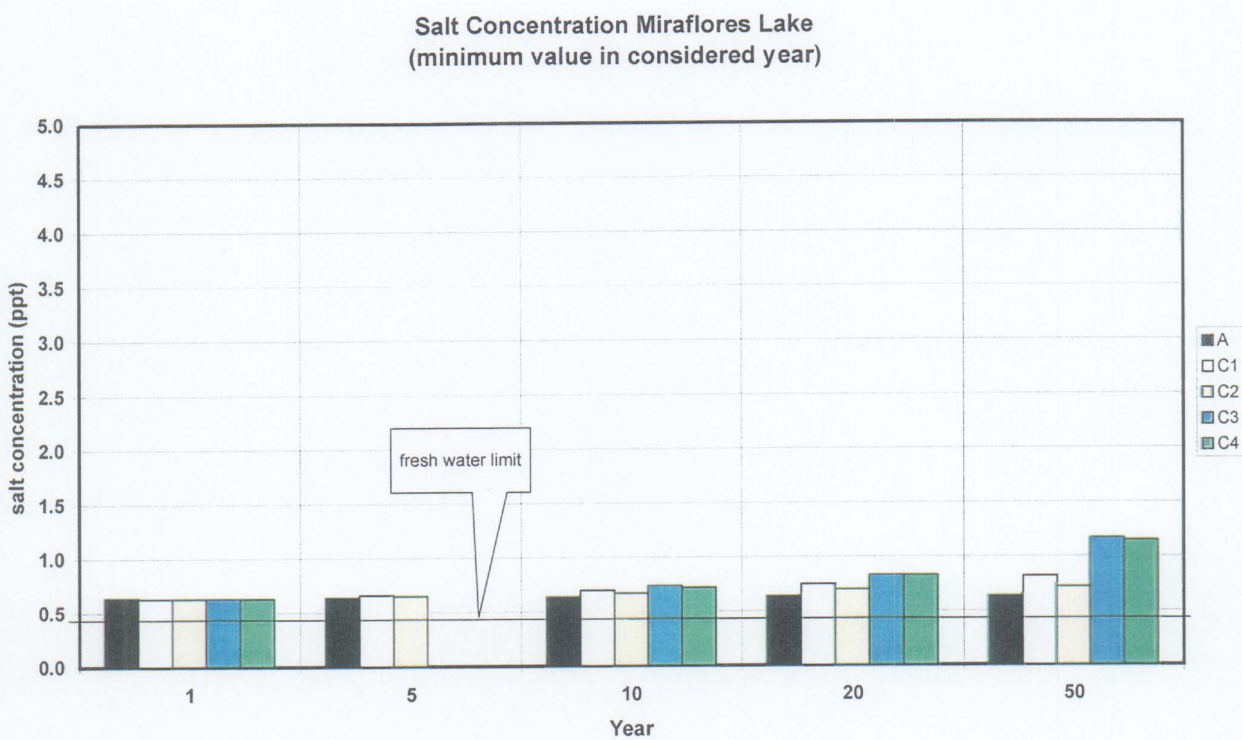
RESULTS OF DELFT3D COMPUTATION EXCHANGE COEFFICIENT, STEP II, NO SHIP	2-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.1

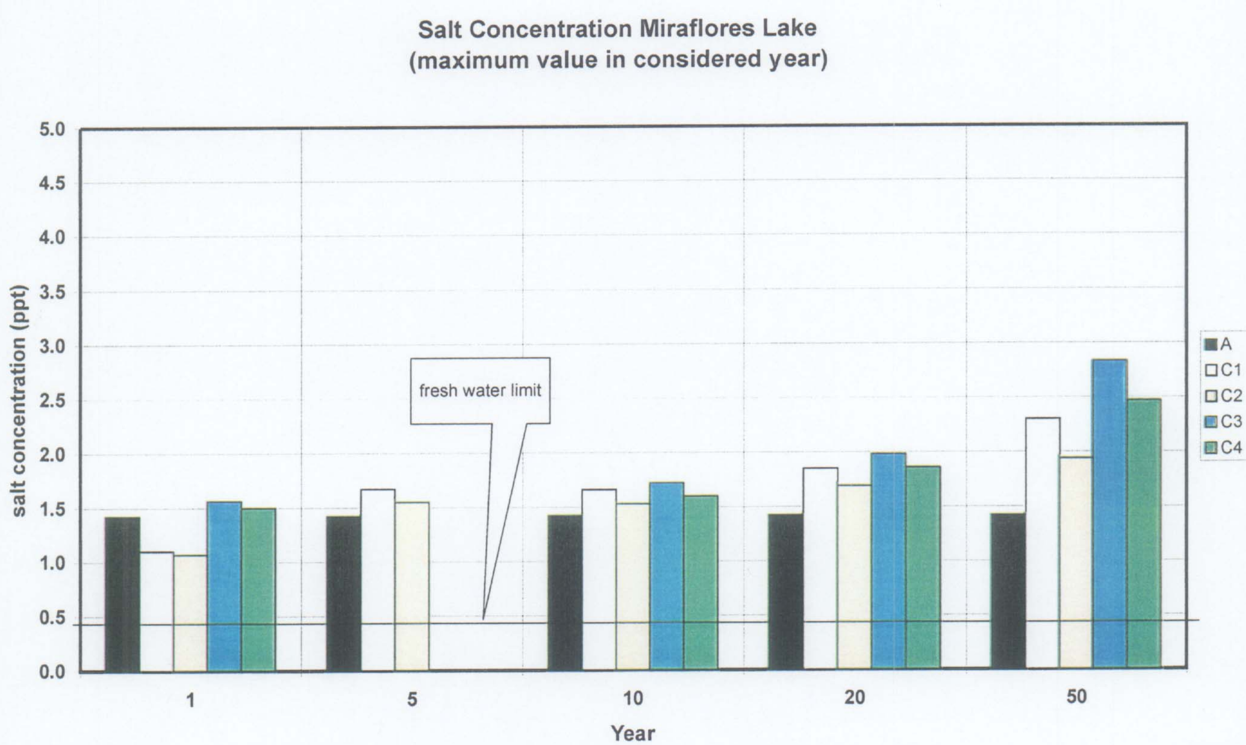


RESULTS OF DELFT3D COMPUTATION EXCHANGE COEFFICIENT, UPLOCKAGE STEP II, SHIP TYPE VII	2-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.2



RESULTS OF DELFT3D COMPUTATION EXCHANGE COEFF., DOWNLOCKAGE STEP II, SHIP TYPE VII		
	2-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.3





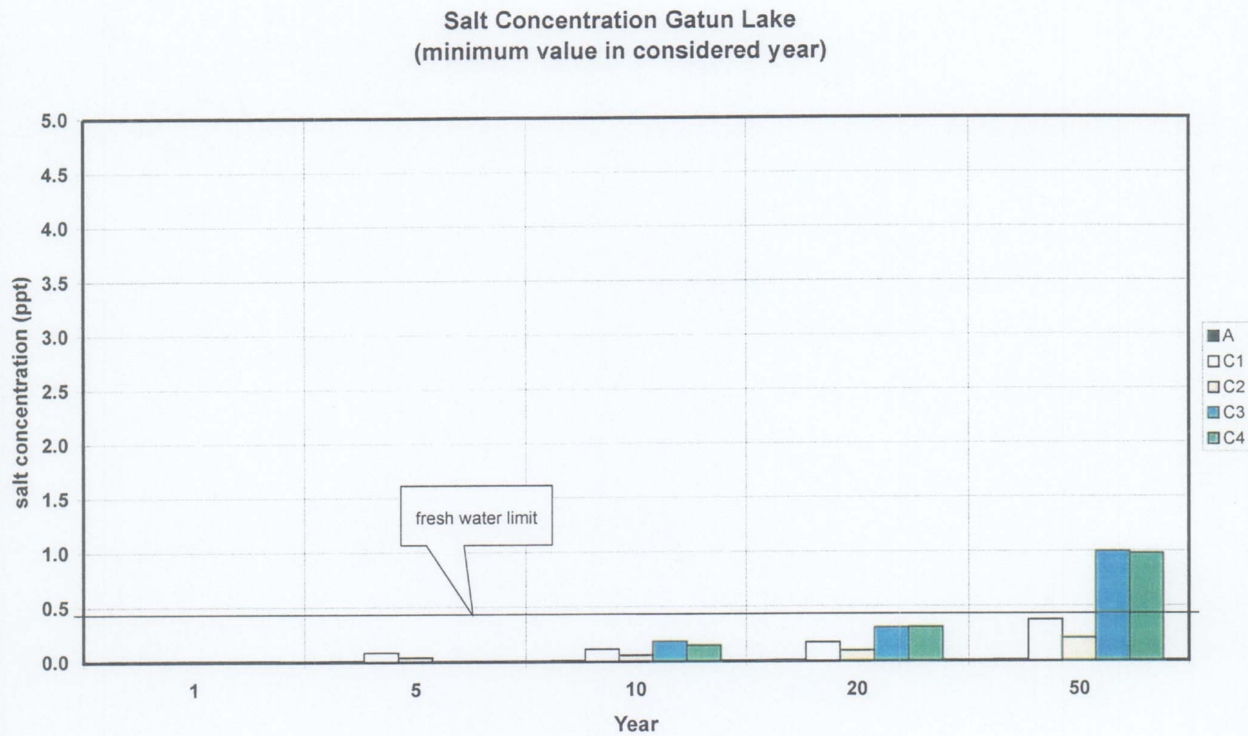
SALT CONCENTRATION MIRAFLORES LAKE
maximum and minimum value in considered year

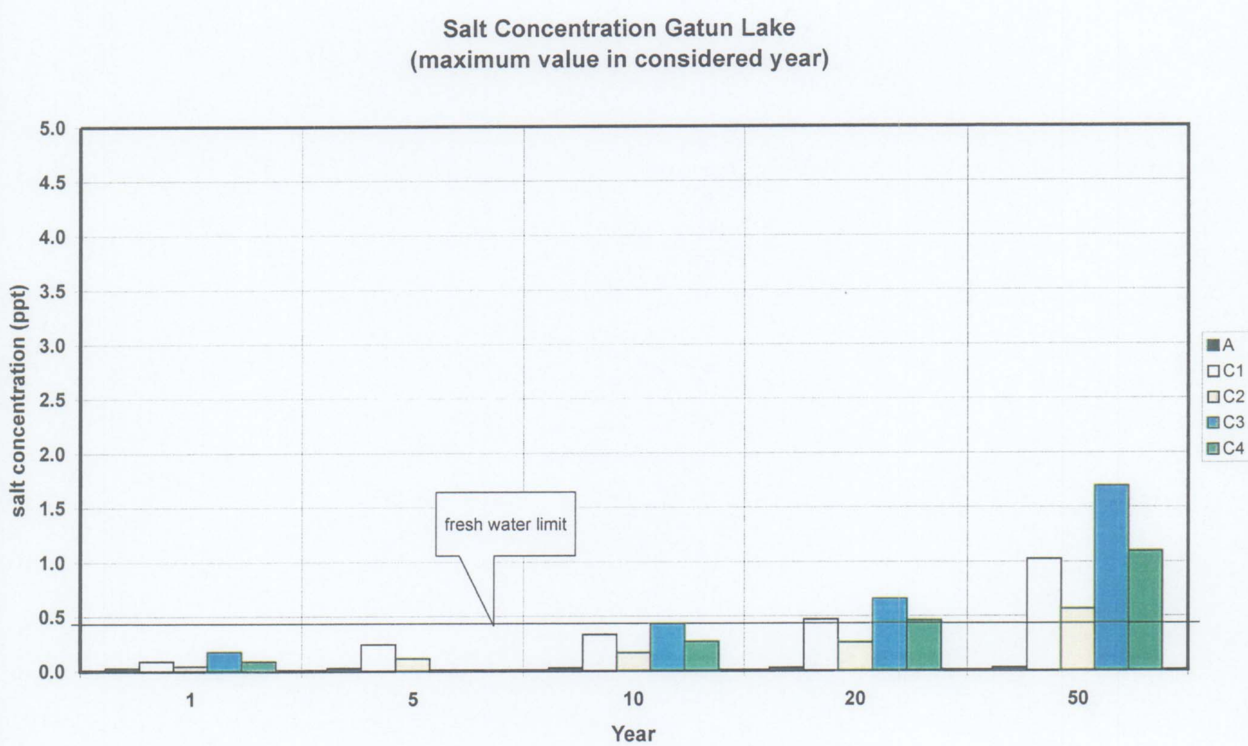
2-lift locks

WL | DELFT HYDRAULICS

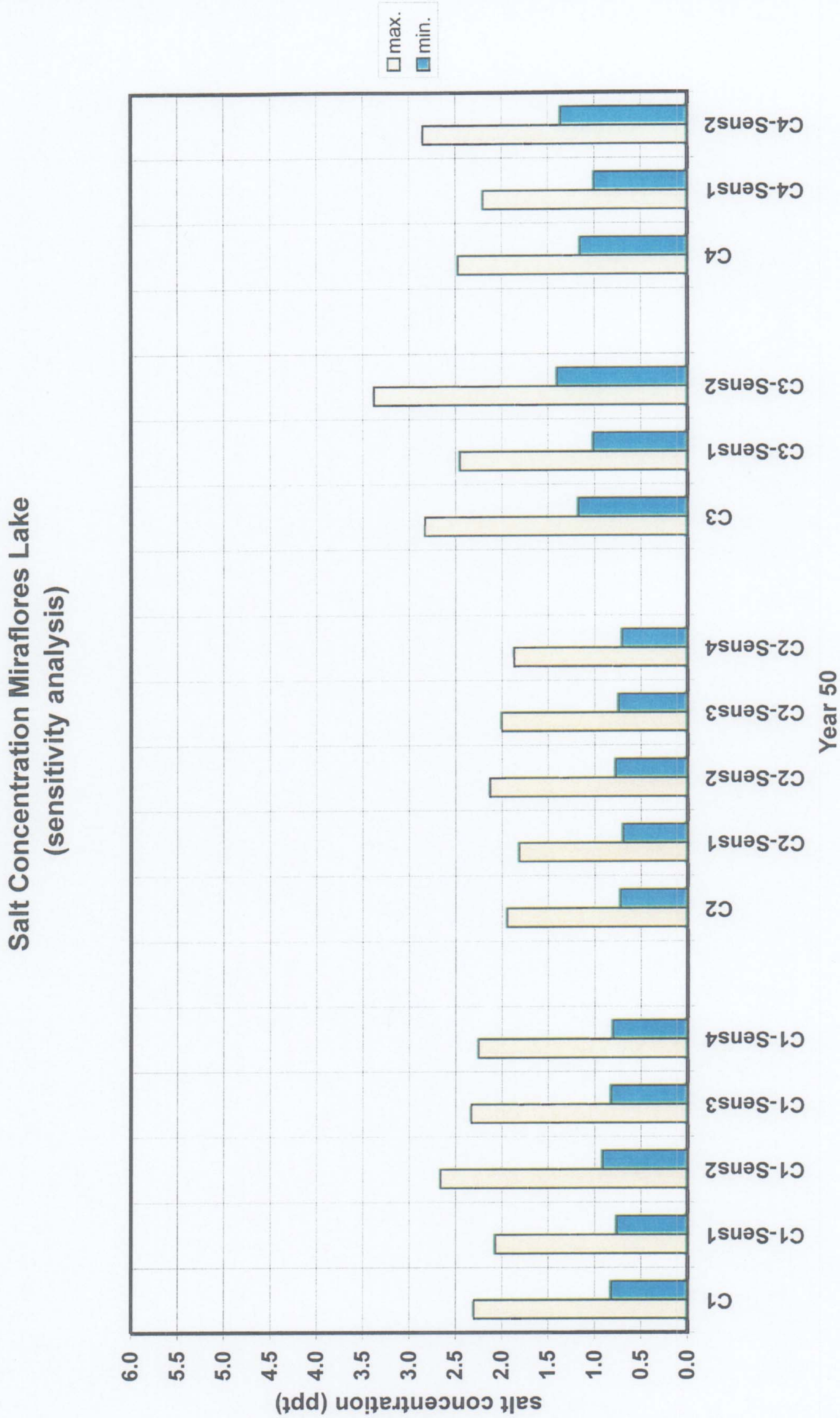
Q 3039

Fig. 7.1

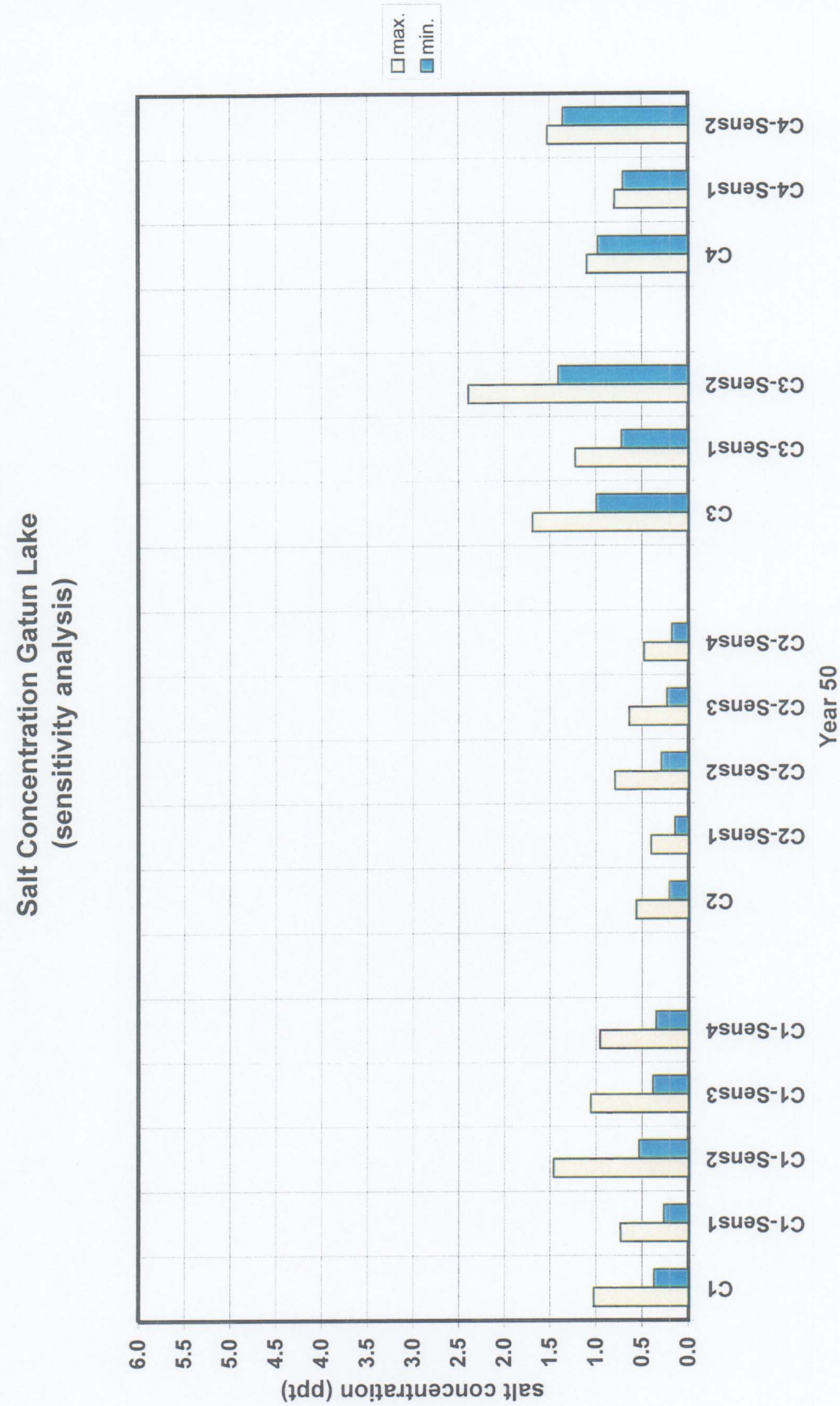




SALT CONCENTRATION GATUN LAKE maximum and minimum value in considered year	2-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 7.2



SALT CONCENTRATION MIRAFLORES LAKE, YEAR 50 sensitivity analysis, various scenarios		
	2-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 7.3



SALT CONCENTRATION GATUN LAKE, YEAR 50 sensitivity analysis, various scenarios	2-lift locks	
WL | DELFT HYDRAULICS	Q 3039	Fig. 7.4

Figures Simulations

Figure A-1, 1 Existing Situation. Case validation. Salt concentration Miraflores Lake after 1 year (output interval: day)

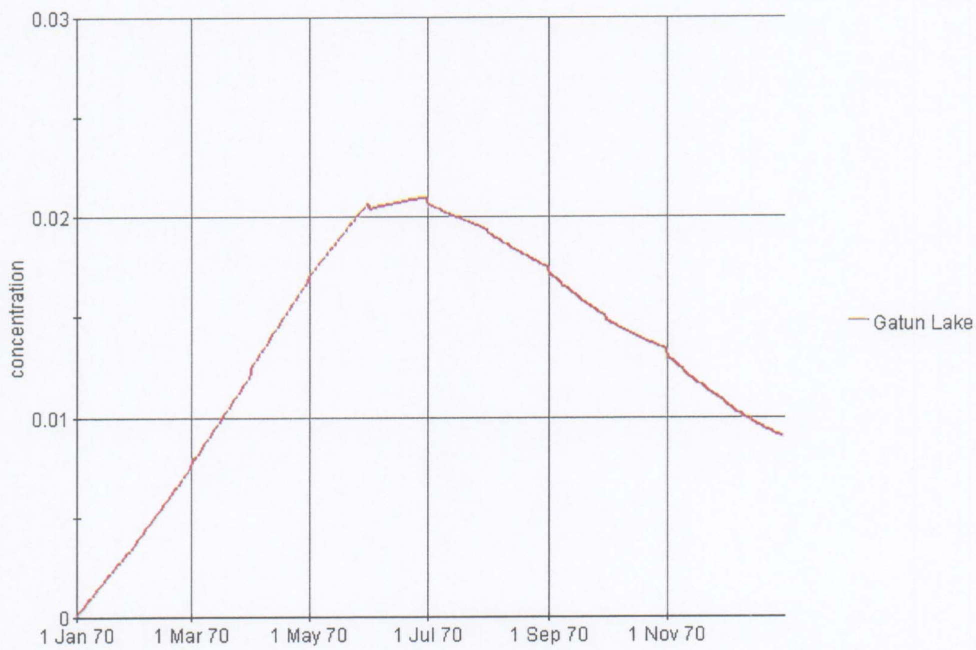


Figure A-1, 2 Existing situation. Case validation. Salt concentration Gatun Lake after 1 year (output interval: day)

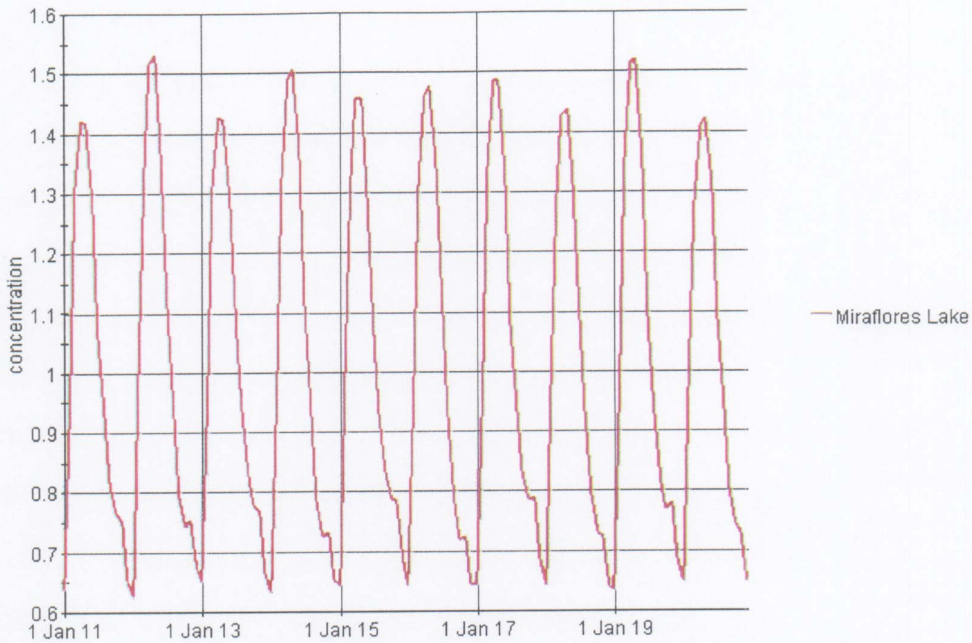


Figure A-10, 1 Case A-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

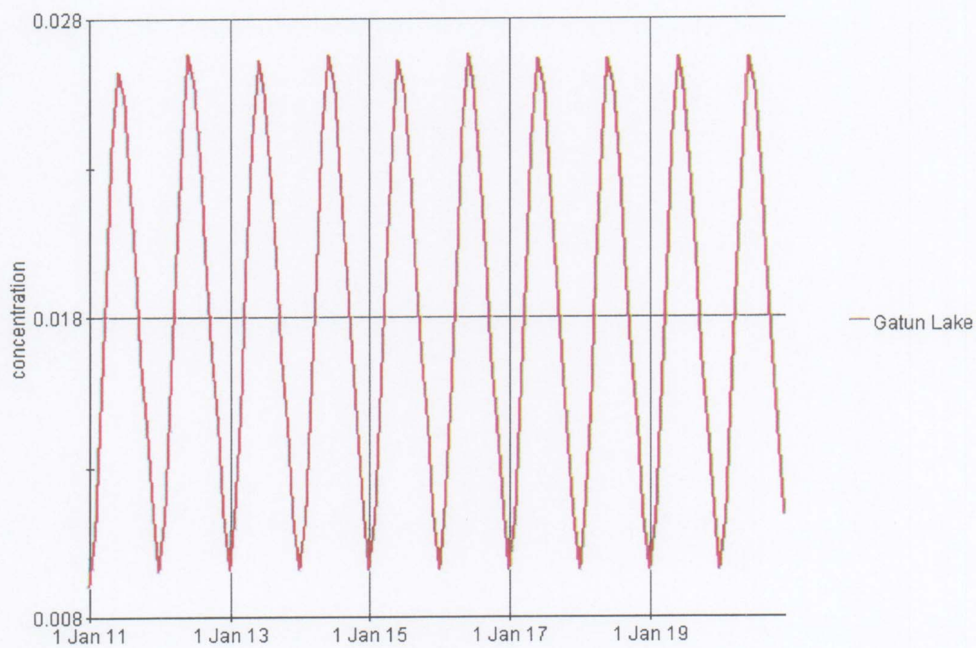


Figure A-10, 2 Case A-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

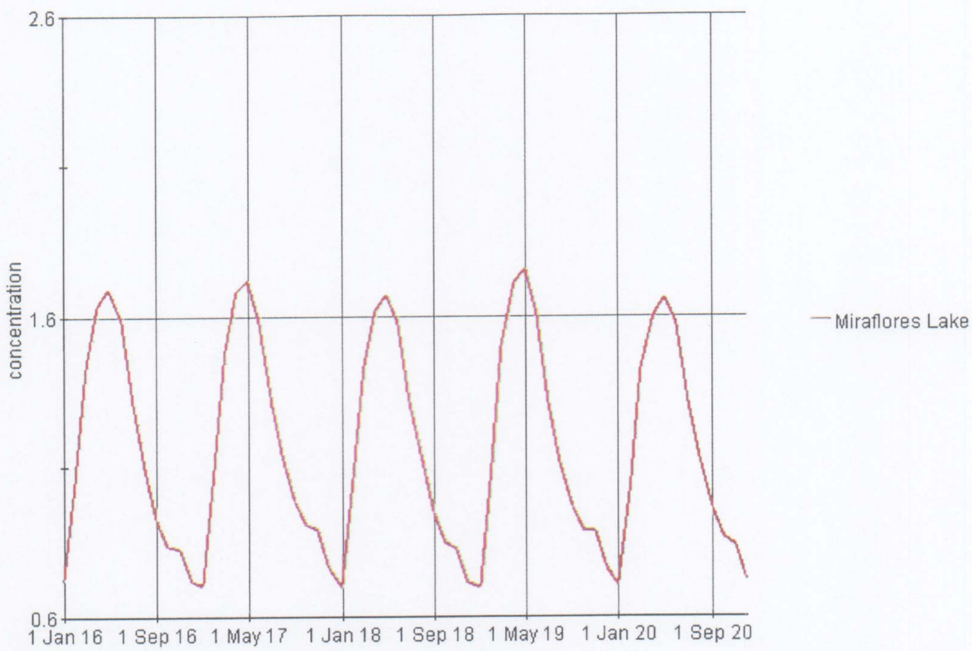


Figure C1-10, 1 Case C1-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

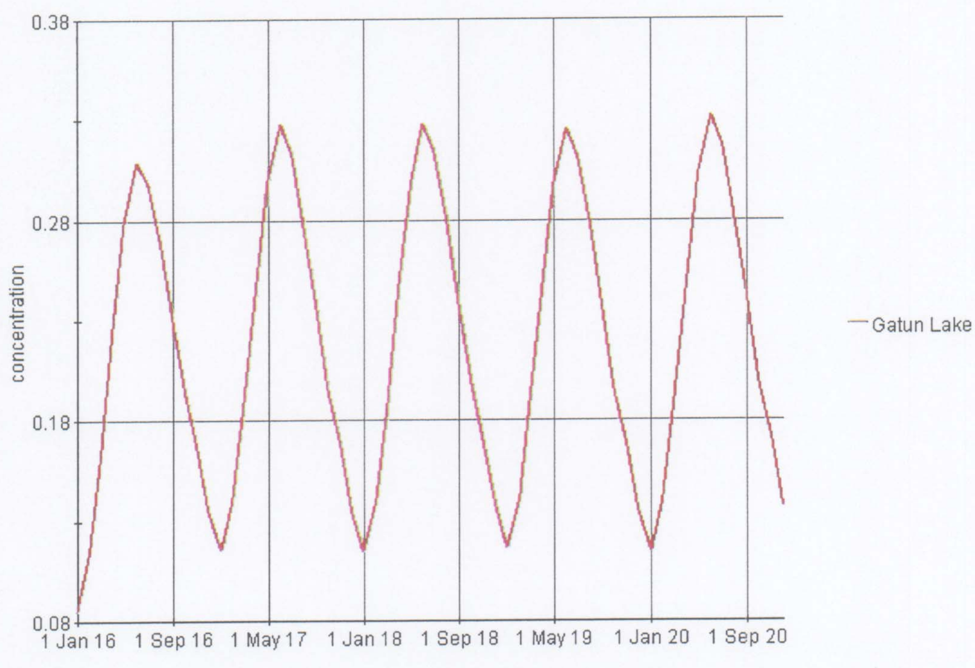


Figure C1-10, 2 Case C1-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

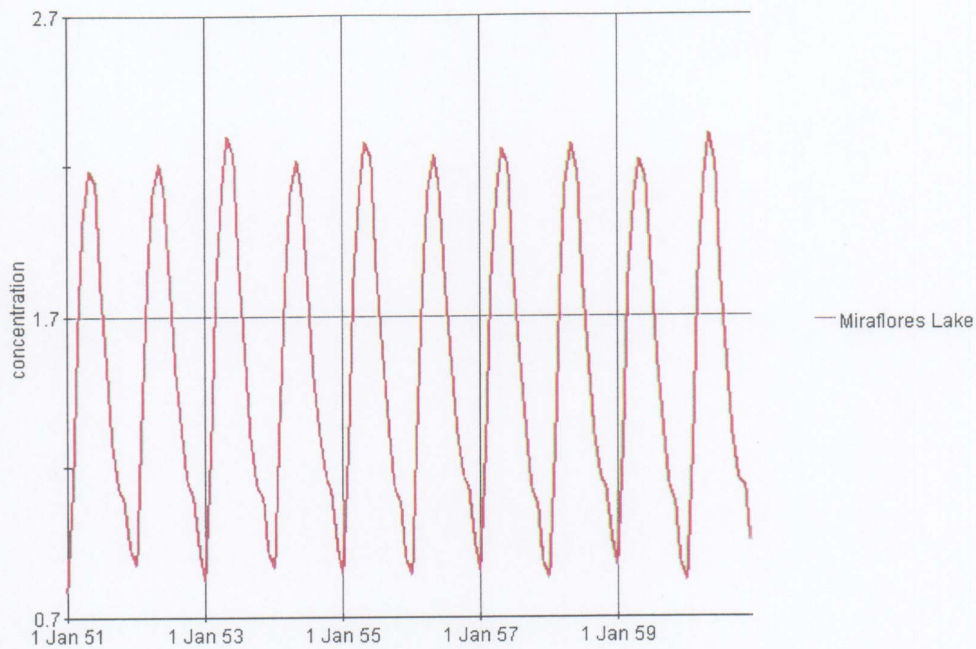


Figure C1-50, 1 Case C1-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

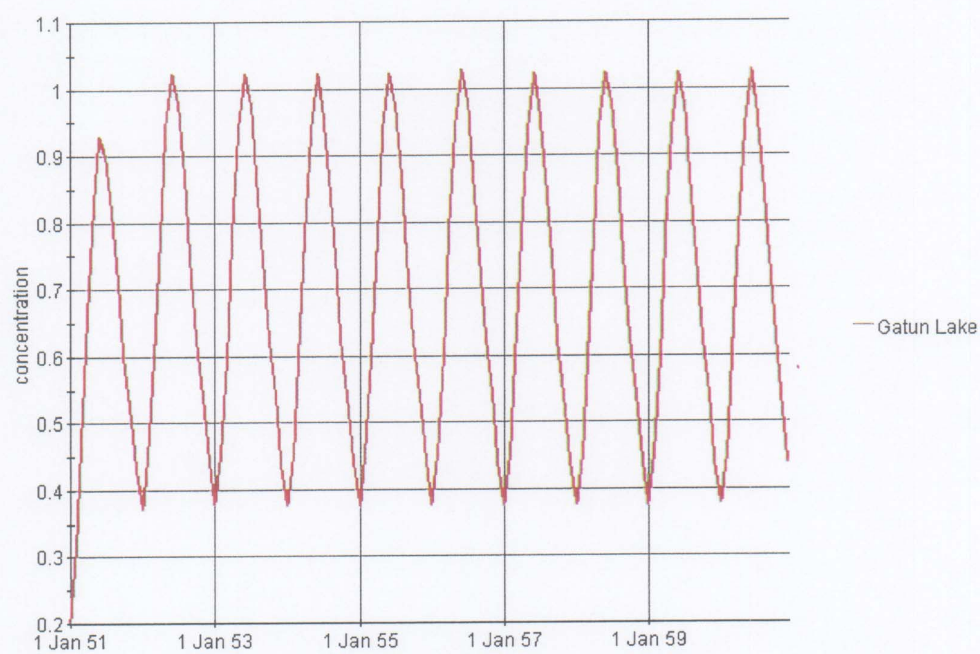


Figure C1-50, 2 Case C1-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

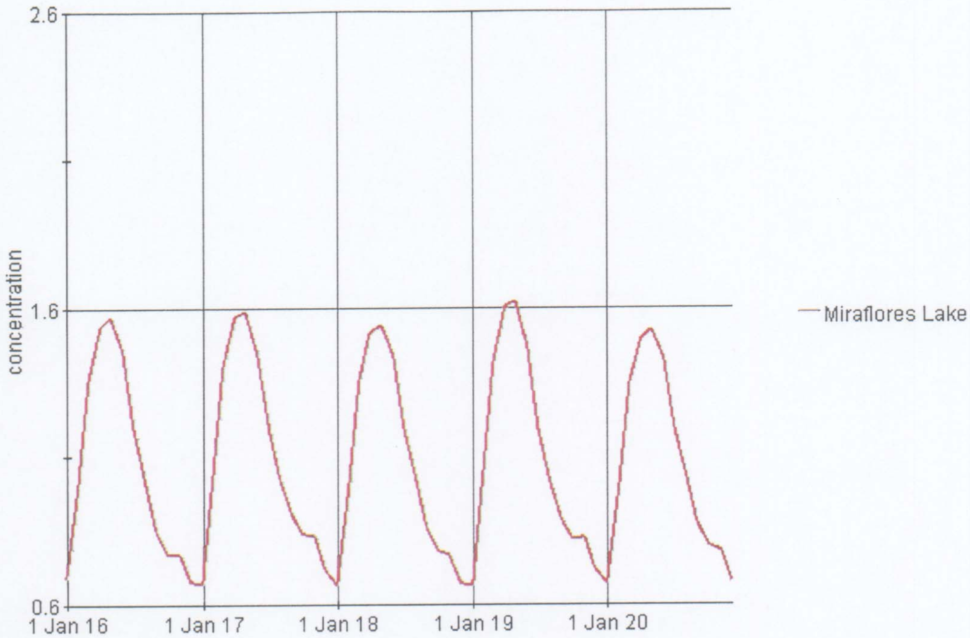


Figure C2-10, 1 Case C2-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

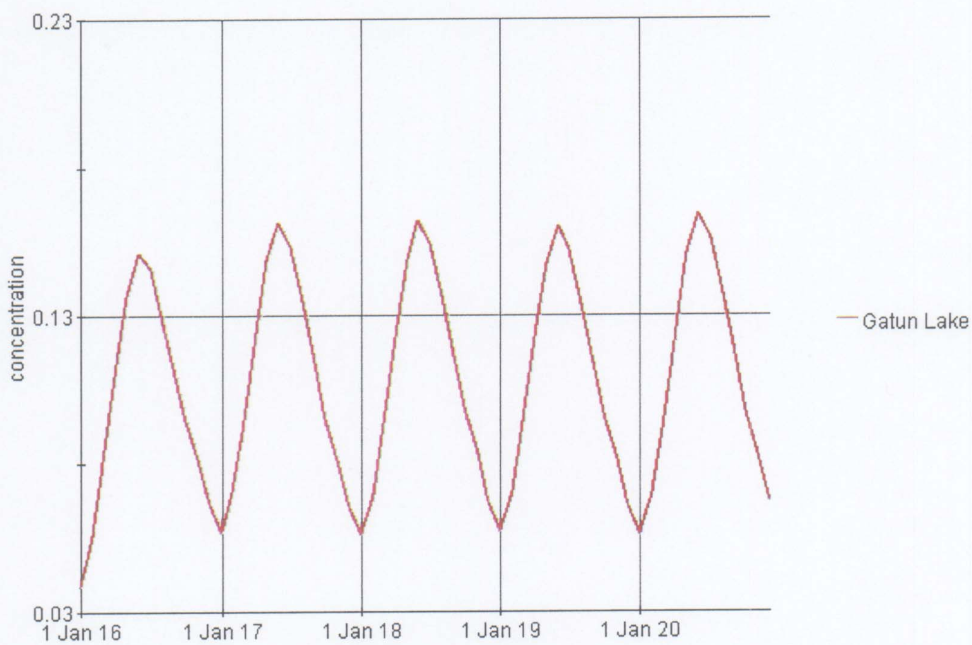


Figure C2-10, 2 Case C2-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

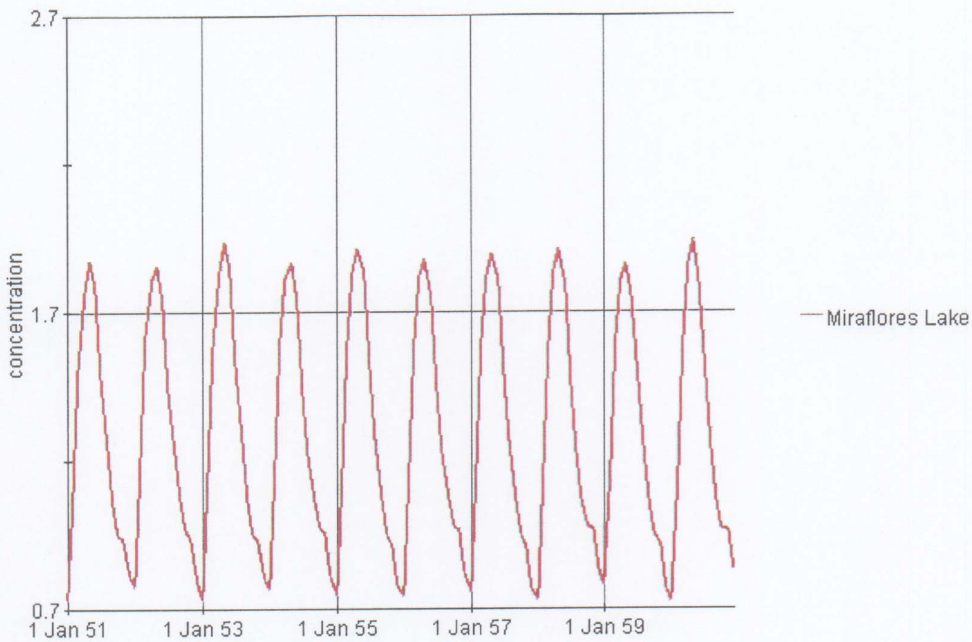


Figure C2-50, 1 Case C2-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

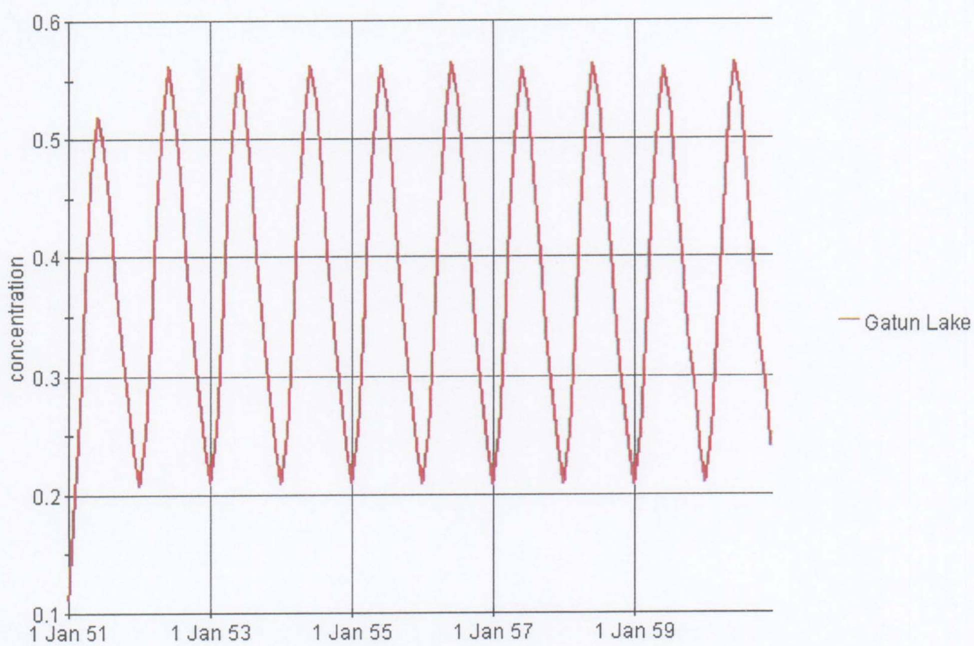


Figure C2-50, 2 Case C2-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

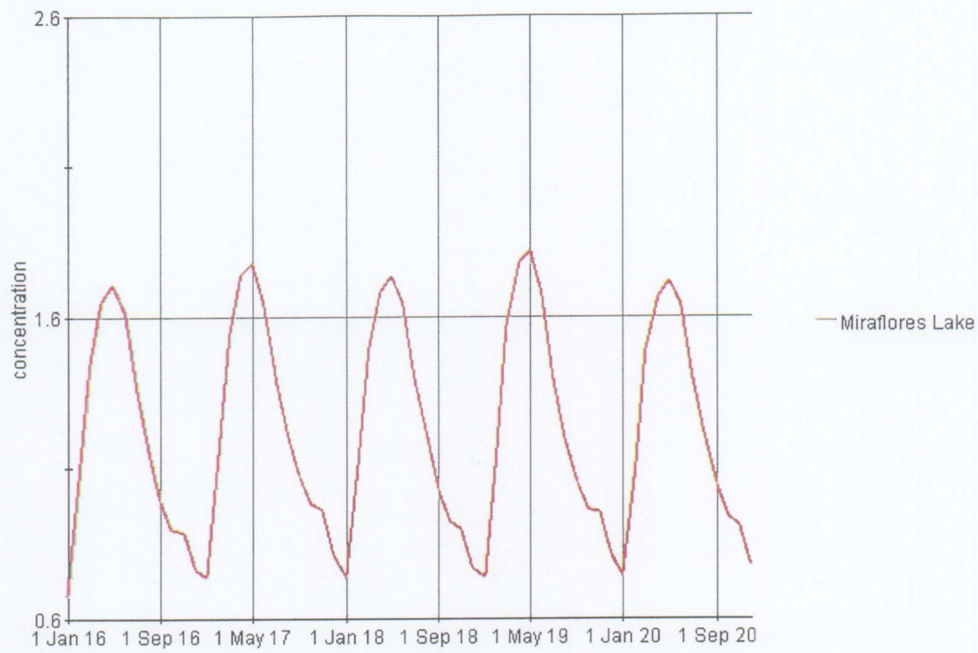


Figure C3-10, 1 Case C3-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

Figure C3-10, 2 Case C3-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

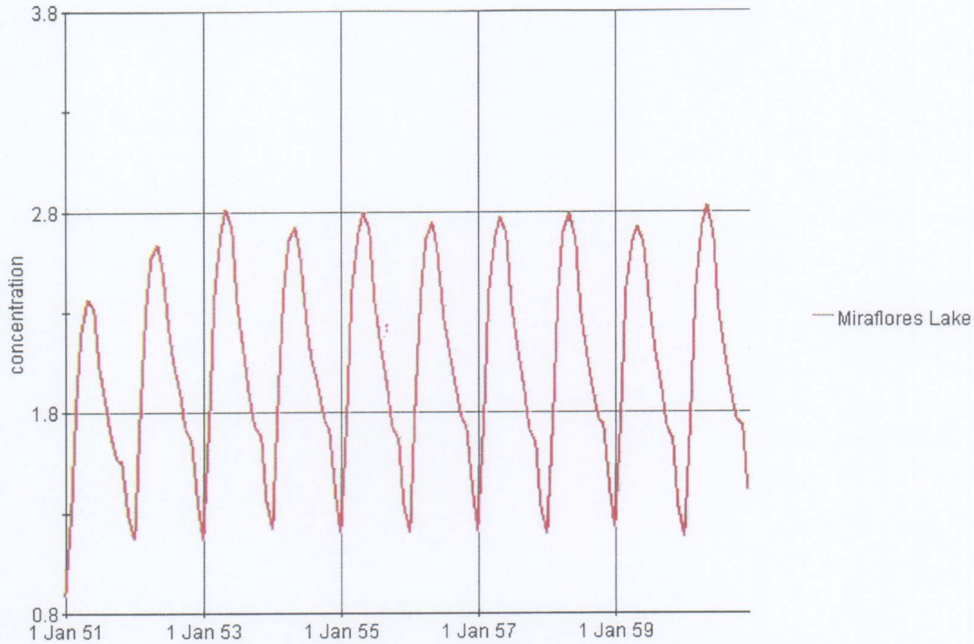


Figure C3-50, 1 Case C3-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

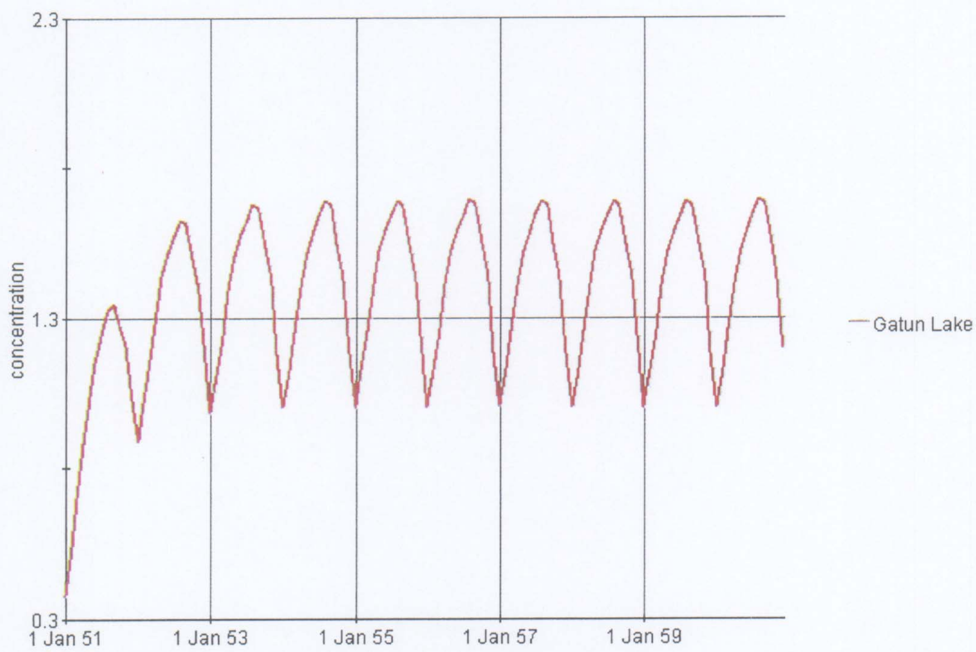


Figure C3-50, 2 Case C3-50. Salt concentration of Gatun Lake after 50 years (output interval: month)

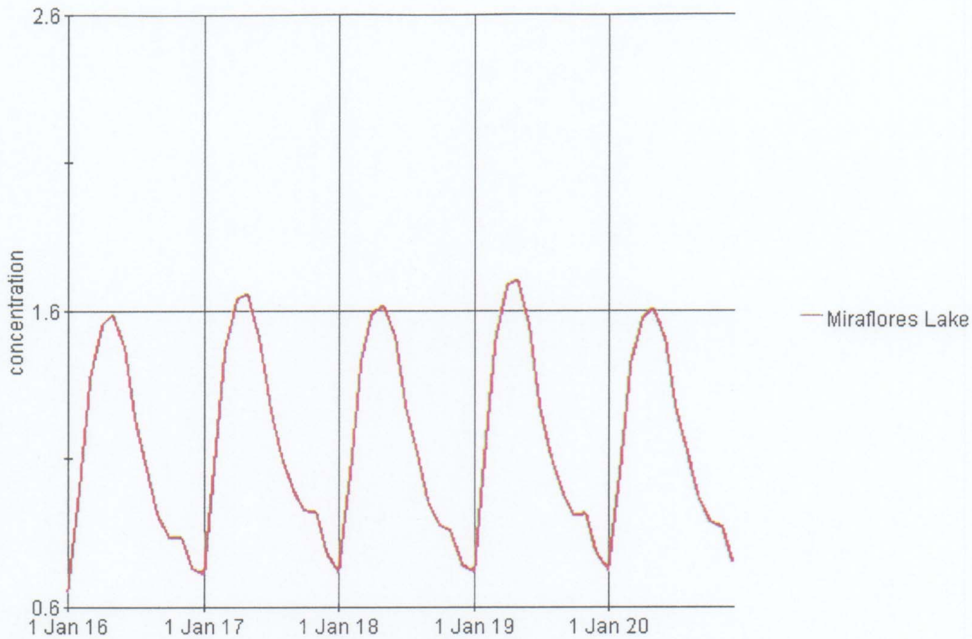


Figure C4-10, 1 Case C4-10. Salt concentration of Miraflores Lake after 10 years (output interval: month)

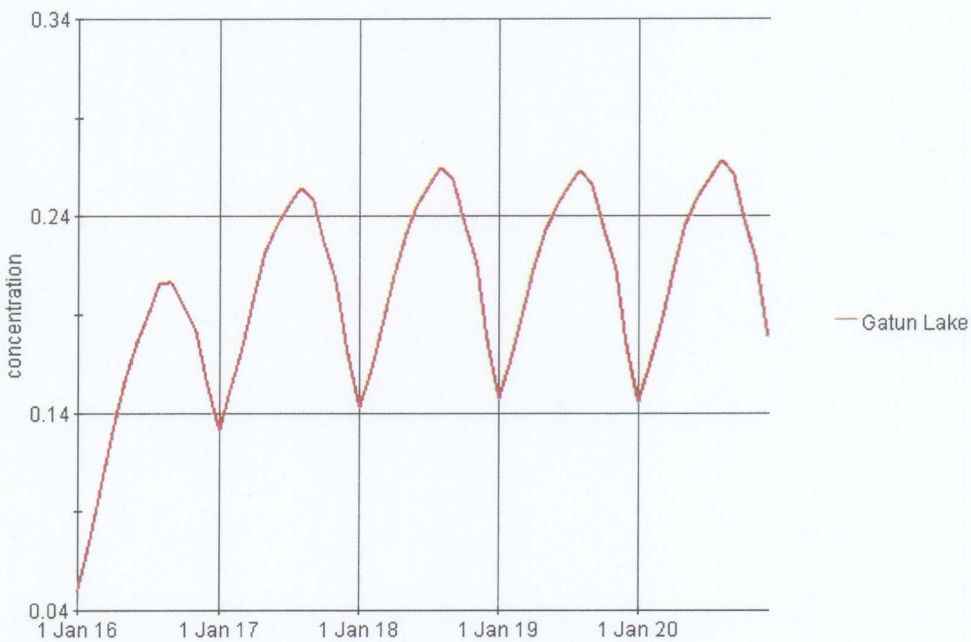


Figure C4-10, 2 Case C4-10. Salt concentration of Gatun Lake after 10 years (output interval: month)

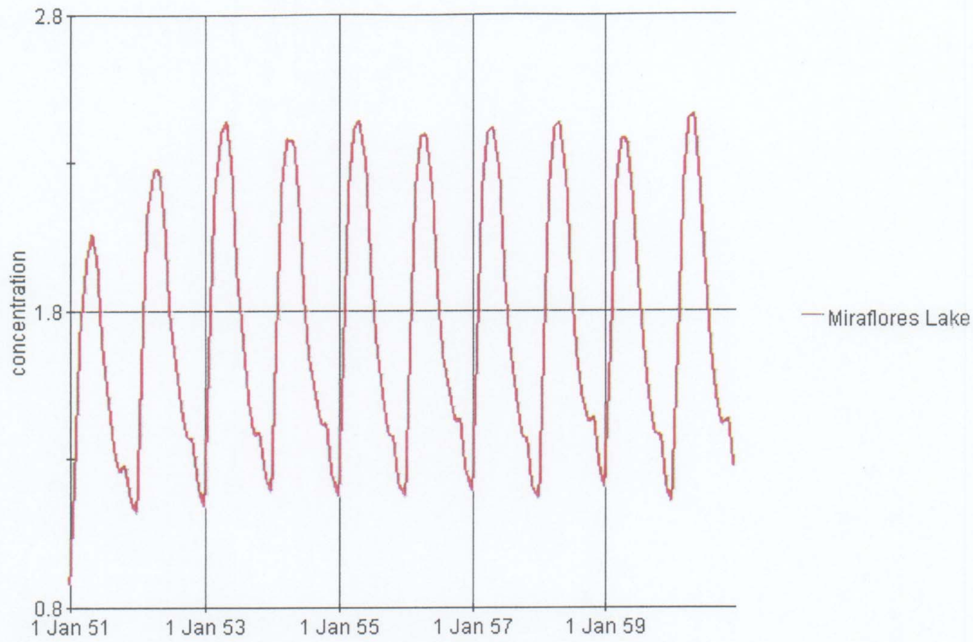


Figure C4-50, 1 Case C4-50. Salt concentration of Miraflores Lake after 50 years (output interval: month)

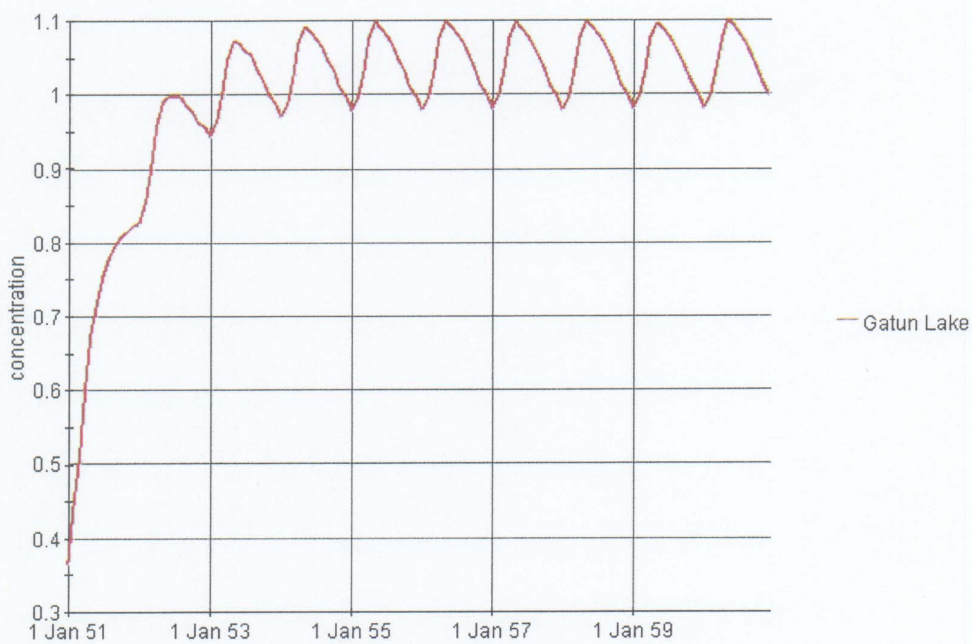


Figure C4-50, 2 Case C4-50. Salt concentration of Gatun Lake after 50 years (output interval: month)