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Autoridad del Canal de Panamá

Salt Water Intrusion Analysis
Panama Canal Locks

Existing situation

Report A: field data collection, development and validation of simulation model, analysis of salt water intrusion

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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 A 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, collection of field data on salinity in wet and dry season, development of a numerical simulation model, analysis of salt water intrusion in the existing situation, and specifications for testing of salt water intrusion in physical scale models

Reports B, C and D present an analysis of the expected salt water intrusion for three different configurations of proposed Post-Panamax locks.

REFERENCES: FMCC -Contract no SAA-74337, signed by ACP on 9 October 2001
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Summary

Introduction

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 objectives of the services of WL | Delft Hydraulics were to analyse the salt water intrusion for the existing and proposed Post-Panamax locks. To that purpose the services included:

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- 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

In addition, the services include:

- 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 A 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, collection of field data on salinity in wet and dry season, development of a numerical simulation model, and analysis of salt water intrusion in the existing situation. In addition, the report presents the specifications for testing of salt water intrusion using scale models (Appendix III).

Review of data

Various reports, drawings, data and brochures on the subject of canal design and operation, salt water intrusion, and future extension of the canal have been provided by ACP. All reports and data, in particular data on the existing canal and lock system and salt water intrusion, have thoroughly been studied.

The Panama Canal, in operation since August 1914, connects the Atlantic Ocean in the north-west with the Pacific Ocean in the south-east. The total length from ocean to ocean is about 80 km. Gatun Lake in the north-western canal area and Gaillard Cut, a narrow channel excavated in the rocks of the Continental Divide, form the highest part of the canal system. Gatun Lake is connected with the Atlantic Ocean by means of a two-lane, three-lift lock system. A two-lane, single-lift lock system connects Gaillard Cut with the relatively small Miraflores Lake in the south-eastern canal area and a two-lane, two-lift lock system connects Miraflores Lake with the Pacific Ocean. From the viewpoint of salt water intrusion

most important features of the locks are the upward step in the floor at the upstream side of each lock, and the floor filling / emptying system. The average step in the water level is between 8.15 m and 9.30 m. The average number of transits (ocean-going vessels) is about 35 per day.

At some occasions in the past salinity measurements have been carried out in the Panama Canal. Also the Environmental Management Division of ACP occasionally executes salinity measurements. The main conclusions that can be drawn from these salinity measurements are:

- The salt concentration in Gatun Lake is almost negligable; Miraflores Lake has a low salt concentration (up to 3 per mille).
- Salt concentrations in the Atlantic and Pacific Entrances are lower than salt concentrations in the oceans, in particular near the water surface near the locks.
- The floor filling system in the locks facilitates a good mixing of fill water with the water in the lock, resulting in a rather uniform salt concentration after filling; mixing is sustained by the propellor action of the sailing ship.
- Density currents and layering occur in the locks when the gates are opened.

Initial qualitative interpretation of salt water intrusion

The salinity measurements which were undertaken in the past indicate that lockage operations cause some salt water intrusion in Miraflores Lake but almost no salt water intrusion in Gatun Lake. Gatun Lake is the highest level, Miraflores Lake is one step below Gatun Lake, and two steps above the level of the Pacific Entrance.
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 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 steps in the floor play an important role in view of a limitation of salt water intrusion from lower basins to higher basins.

In the case of uplockage the ship is in the lock chamber that is filled with water from the higher adjacent basin. Initially the water volume in the lower lock is relatively small compared to the ship's submerged volume. The inflow of water through jets is influenced by the ship that floats above the fill openings. When the adjacent high basin is a lock, water is drawn from an initially large water volume (without ship), and initial inflow velocities in the jets may be high because of the initial great water level difference. When the adjacent high basin is a lake, water is drawn from the area between the side wall and the centre wall, near the upstream gates. When the water levels in both basins have been equalized and the upstream gates are opened, the ship has to pass the step in the lock chamber floor (except when the low basin is the sea entrance or a lake). The keel clearance at the step is of importance for return currents and possible piston effects (water in the high lock may be set up).

In the case of downlockage the ship is in the lock chamber where the water is drawn to fill the low basin. When the low basin is a lock, the filling jets are not blocked by a ship and can freely expand. Initially the fill water with - most probably - a lower density widens and spreads near the water surface. Because many jets are present spreading is limited and fill

water expands in upward and downward direction, the latter because of an intensive mixing due to the jet-generated turbulence. When the ship sails from the high basin to the low basin it passes a downward step (except when the low basin is the sea entrance or a lake). Again the keel clearance at the step is of importance for return currents and piston effects (the water level in the adjacent high lock may be drawn down).

The various steps in uplockage and downlockage can not fully be simulated in a three-dimensional numerical flow model. Instead, a simplified simulation model has to be applied in which exchange coefficients are used to quantify the exchanged water volumes between separate basins with different salinities. These exchange coefficients are, in general, different for the various steps in the lockage process and vary in dependence of several influencing factors.

Field data collection

Field measurements were required to collect sufficient data for the study of salt water intrusion in the Panama Canal. The field-data collection programmes were such designed that, in particular, data were obtained for the analysis of the physical processes during uplockage and downlockage, while also data were collected for the determination of exchange coefficients for use in the numerical model, that simulates the process of salt water intrusion. In addition, present salinity levels in Gatun Lake and Miraflores Lake were measured as well as salinity levels in the sea entrances.
Panama has two seasons, the wet season from mid May to end of December and the dry season from January to mid of May. Since seasonal variations (variation of water level in Gatun Lake caused by seasonal variation of precipitation, variation of water release from the lakes, seasonal upwelling of colder and more saline water at the Pacific Coast during the dry season) were regarded as possible influencing factors for the process of salt intrusion, measurements have been executed by the end of the wet season and the dry season.

Measurements of vertical salinity profiles in lock chambers, forebays, tailbays, lakes and sea entrances have been carried out with two, fast response CTD instruments (CTD = conductivity, temperature and depth below water surface). From these measurements both the salinity and the density can be derived as a function of depth below the water surface.
The two CTD's were deployed in the locks, the canal area and the sea entrances, using two small survey boats (launches Cara Cara and Perico), which were made available by ACP. A third, CT-instrument connected to a data logger, was put into service to measure the salinity at a number of well chosen, fixed locations, in the forebays and tailbays of the locks, both at the Pacific side and the Atlantic side. The work in the locks and channels was coordinated by ACP staff.

Qualitative interpretation of salt water intrusion in existing situation

Pacific and Atlantic Entrances
Measurements in the *wet season* show that an underlayer exists in the Pacific Entrance with a constant salinity; the salinity is about 28 ppt in the area near the locks. Spillages from the locks cause lower salinity values in a layer near the water surface. The thickness of this upper layer depends mainly on the number of lockages at Miraflores and on pauses between lockage periods. The considerable tidal variation in the Pacific Entrance seems not very

important for the salinity levels in the area near to the locks. It is true that the tidal movement causes an inflow and outflow of water in the sea entrance, but horizontal tidal flow velocities near the locks are small and do not cause an important mixing up. As a result, only the thickness of the lower layer where the salinity has a more or less constant value of about 28 ppt varies with the tidal movement. The temperature in this underlayer is about 28 °C. Measurements in the *dry season* show that the temperature in the underlayer is considerably lower, about 21 °C, while the salinity is higher, about 34 ppt. Probably, these differences are caused by seasonal variations in the upwelling flows towards the Pacific coast.

Measurements in the Pacific Entrance show that an underlayer exists, similar as in the Pacific Entrance, where the salinity and temperature have a constant value. In the *wet season* the salinity in the underlayer near the locks was about 31 ppt, in the *dry season* a little higher about 32 ppt. The temperature of the water in the underlayer was more or less the same in both seasons, about 28 °C. Similar as in the Pacific Entrance the thickness and the salinity of the top layer vary in dependence of the distance to the locks. Salinity fluctuations in the top layer are caused by the continuous, but interrupted spill flows from Gatun Locks.

Salt water intrusion process in locks

Extensive measurements have been executed in the locks, forebays and tailbays. From the analysis of the measurement data and visual observations some characteristic hydraulic processes have been identified with respect to the intrusion of salt water during uplockage and downlockage of ships. General conclusions based on the salinity measurements are: (i) important transverse density phenomena do not occur in the lock chambers, (ii) average salinity levels decrease considerably in each higher lock chamber, and (iii) a more or less cyclic pattern of salt water intrusion may be expected, which is caused by alternate periods of uplockage and downlockage of ships.

Layering and density waves are normal hydraulic phenomena in closed lock chambers, while density currents between adjacent basins occur when gates are open. Table 3.4, which is based on the results of our measurements, presents the approximate range of volume-averaged salinity values in the various basins.

There are several apparent differences between uplockage and downlockage. Key notions are: an upward movement of the ship goes together with a downward movement of water, a downward movement of the ship goes together with an upward movement of water; fill water is always going downward; fill water dilutes, and fill jets mix up the water in a lower lock chamber; the step in the floor at the upstream side of the lock chambers influences the currents driven by density differences, and limits the salt water intrusion.

The uplockage process starts in a lower lock, that for the greater part is filled with saline seawater; this holds in particular for the locks at the Pacific side where lock gates are opened far before the ship arrives. When the ship enters, a quantity of water equal to the submerged volume of the ship is pushed away and flows out to the seaside tailbay. Due to density effects and the movement of the ship an additional exchange of water between the lock and the seaside tailbay occurs: water with lesser salinity moves to the seaside tailbay and is replaced by an almost equal quantity of water with higher salinity, causing salt water intrusion. This process repeats in each higher lock, but the upward step at the entrance of a higher lock together with the return current along the ship are effective means to limit the salt water intrusion. Moreover, fill water from the higher adjacent lock is drawn from the water region near to the floor, which has the highest salinity, or from the forebay. In this way

salt water will be sluiced back. A disadvantage of the floor filling system is that the filling jets mix up the entire water volume around the ship in a lock chamber; in view of a prevention of salt water intrusion to the adjacent higher basin this is unfavourable.

The adverse effect of the filling jets is especially clear during downlockage of a ship. Starting with the upper lock (no ship in the lock chamber), water is filled from the forebay. A part of the earlier intruded salt is drained back with the fill water. The water in the lock chamber is diluted by the supply of this water that, generally, has a lesser salinity than the receiving water in the lock chamber. However, the filling jets mix up the entire water body. As a result higher salt concentrations are also present in the upper part of the water body, near the water surface. When the ship enters, a water quantity equal to the submerged volume of the ship is pushed away and flows back to the forebay. This water has it's origine mainly in the upper region of the water in the lock chamber, and because of the intensive mixing process it contains salt. Density differences and the movement of the ship cause an additional exchange of water between the lock chamber and the forebay. In this situation the downward step at the entrance to the lock chamber is less effective in the prevention or reduction of salt water intrusion. This process repeats in each next lower lock. The tide in the sea entrance is in particular of importance for the last phase in the downlockage process, when the ship enters the lower lock adjacent to the seaside tailbay. At high tide the water level in this lock is high and consequently only a relatively small quantity of fill water is required to level up. The water in the lower lock is thus less diluted, and water with a higher salt concentration intrudes in the adjacent higher lock. Contrary, low tide in the sea entrance causes a lesser salt intrusion.

Generally spoken, more salt is transported in upstream direction during downlockage than during uplockage. Possibly, in some cases even a negative transport may occur during uplockage. High tide is more unfavourable for salt intrusion than low tide, both at uplockage and downlockage. Bigger ships cause a greater return current and are thus unfavourable in the case of downlockage; smaller ships cause a lesser return current but because of that the development of density flows is less hampered, and becomes mainly a function of time. Smaller ships come in groups, and require more time for operation. As a consequence, gates may be open during a longer period of time, which is unfavourable in view of a prevention of salt water intrusion.

Miraflores Lake

Lockage operations at Pedro Miguel are the reason that Miraflores Lake is fed with a more or less continous spill flow from Gatun Lake. Rainwater enters at several locations along the west and east bank. Evaporation and lockage operations at Miraflores cause water losses. The drain water quantity at Miraflores Locks is somewhat smaller than at Pedro Miguel Locks. Surplus water is spilled through the spillway beside Miraflores Locks. This is also the location where water is drawn for cooling water purposes. As a result a flow circulation pattern exists with a net flux in southern direction towards Miraflores. In the dry season water supply to the lake is for the greater part caused by lockage operations at Pedro Miguel. The water level in Miraflores Lake is maintained at about PLD +54.5 ft (PLD +16.6 m) throughout the year.

Measurements in the wet season show that the average salinity is about 0.5 ppt in the entire shipping channel between Miraflores Locks and Pedro Miguel Locks. Near the bed salinity

values are up to about 1.5 ppt (smaller values up to about 1.0 ppt are found near Pedro Miguel Locks, while salinity values near the water surface may be smaller than 0.5 ppt).
Detailed measurements in sections near Miraflores Spillway show salinity values between about 0.3 ppt near the water surface and 0.8 ppt near the bed.
Measurements in the dry season in the shipping channel show that the salinity is about 1.3 ppt near the water surface in the area of Miraflores Locks, going down to about 1.0 ppt near Pedro Miguel Locks. In the water region above the bed salinity values are higher; they vary roughly between 2.0 ppt and 3.5 ppt in the entire channel. Measurements in the area near Miraflores Spillway show salinity values between about 1.2 ppt near the water surface and 1.5 – 2.5 ppt near the bed.
The salinity values which are found near the bed in the area near the spillway are generally smaller than the values found near the bed in the shipping channel. This may indicate that the salt water, intruded through Miraflores Locks, initially propagates in the deeper area of the shipping channel. It is than subjected to a diffusion process and finally flows with the dominant stream pattern to the spillway. In periods that the spillway of Miraflores is active a part of the salt water from the locks may also directly flow to the spillway.

When wet-season and dry-season results are compared it appears that the salinity in Miraflores Lake has become higher in the period between the two measurement campaigns (volume averaged salinity wet season about 0.7 ppt, dry season about 1.5 ppt). Probably, the higher salinity in the dry season is a seasonal effect caused by a lesser release of surplus water at Miraflores Spillway. But also the lower temperature and the higher salinity of the water in the Pacific Entrance in the dry season play a role, because the temperature difference between Miraflores Lake and the sea entrance and the greater salinity difference cause stronger density currents, and thus a greater inflow of salt water.

Gatun Lake
Gatun Lake receives water from Chagres River (Madden Lake) and other rivers. The water level fluctuates in dependence of wet and dry season; the mean water level is PLD +85.0 ft (PLD +25.9 m). Lockage operations at Pedro Miguel and Gatun and evaporation cause a loss of water. Surplus water is spilled at Gatun Spillway; water is also drawn at this location for power generation. The water circulation pattern is towards Pedro Miguel Locks in the southern part of Gaillard Cut and towards Gatun Locks and Gatun Spillway in Gatun Lake.

Measurements show that the salinity is almost zero in the entire shipping channel between Gatun Locks and Pedro Miguel Locks and in the deeper areas near the east bank of the lake (where ships berth) and near Gatun Spillway. In the areas near to Gatun Locks and Pedro Miguel Locks small salinity values are found; occasionally values up to about 0.1 ppt are found in the forebays near the bed. The applied CTD's have a lower measurement limit of 0.1 ‰ salinity; this makes salinity measurements below a value of 0.1 ppt unreliable. A safe conclusion is therefore that the salt concentration of Gatun Lake and Gaillard Cut was smaller than 0.1 ppt during the measurements in wet and dry season.

Simulation model for salt water intrusion

The salt water intrusion process through the locks on the Panama Canal is simulated with a numerical 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.

The simulation model has been set up to predict 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. The 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. This 3d-flow model may use the salt water load caused by the operation of existing and Post-Panamax Locks as input.

The separate basins of the Panama Canal (lock chambers, 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 5.1. In the future a new lane may be opened with locks suited for Post-Panamax vessels.
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. 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. 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.
The subsequent steps of a ship movement are described in a scenario; special scenarios are scenarios that describe a so-called 'turn around' or water releases at Gatun Dam and Miraflores Dam. Scenarios are combined in a day pattern. A normal day pattern consists of a number of ship-movement scenarios, turn-around scenarios and water-release scenarios.

Day patterns are combined in a case. At the start of each case nodal status parameters are initialized. Day patterns are handled one by one in the sequence of input. After handling of the last day pattern the simulation model starts again with the first day pattern; this cyclic process continues untill the end date of the simulation. At the end of each calendar day (or as desired: week, month, year) the computed value of status parameters is written to a file.

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.

Exchange coefficients

The locking process is simulated in the numerical model as a series of subsequent steps. Both the water flows and the salt flows are computed in a step. Salt concentrations in the salt balance are defined as volume-averaged values (in basins); the salt concentration multiplied by the water volume represents a certain quantity of salt. The salt exchange (SE) in the salt balance represents the quantity of salt (kg) that is transferred from one basin to another. The salt exchange SE is expressed as the product of a well-defined reference volume V_{ref}, a salt concentration (or salt concentration difference) related to this reference volume, and an exchange coefficient e_x. For full details reference is made to Section 5.8.
Exchange coefficients represent the combined effects of hydraulic and geometrical aspects related to the various steps during uplockage and downlockage. Most important aspects are: sailing direction of the vessel (uplockage or downlockage), vessel dimensions in relation to lock dimensions, step in floor at the upstream side of locks, density differences between adjacent basins, occurrence of layering and density waves in locks, mixing caused by filling jets and propellor action, and time that lock gates are open.

Exchange coefficients have been derived on the basis of the salinity measurements in wet and dry season, in order to take into account all relevant hydraulic aspects. The derivation of exchange coefficients was sustained by some computations with the Delft3D numerical programme. In addition, maximum and minimum values have been derived through a theoretical analysis. These upper and lower limits appeared to be useful in selecting representative values for the exchange coefficients. The selected exchange coefficients have a constant value in step I of the lockage process (equalize water levels) and are a function of the ratio S/V_{ref} (S = water displacement of ship, V_{ref} = reference volume) in step II (movement of the ship from a basin to the adjacent basin). Geometrical aspects are included in the choice of the exchange coefficients as well as ship dimensions and blockage ratio aspects.

Testing and validation of the simulation model

Testing

We have checked the proper functioning of the simulation model by running several test cases. These test cases were such designed that results could be checked step by step.

A first series of tests was done with the salt concentration of all basins (including Pacific and Atlantic tailbay) set on 0. The purpose of these tests was to check the handling of water levels, water volumes and water balance when ships move from ocean to ocean.
A second series of tests was focused on the proper functioning of spillways, handling of water balance and salt balance, use of coefficients, time-dependent exchange of salt water between forebays / tailbays and lakes and salt-migration process. The initial salt concentration in all basins was set on 0 (including Pacific and Atlantic tailbay), but the initial salt concentration of Gatun Lake and Miraflores Lake was set on 30 ppt.

The last series of tests was focused on the process of salt intrusion from Pacific and Atlantic Ocean. In the simulation runs the salt concentration in the tailbays at the Pacific and Atlantic side was set on a constant value of 30 ppt, while the initial concentration in all other basins was set on zero.

In this testing process errors were detected and corrected. With the final version of the simulation model validation runs were executed.

Validation

The simulation model was validated on the basis of the salinity measurements in wet and dry season. Volume averaged salinity values found in the lakes were used for calibration of the model (Gatun Lake: volume-averaged salt concentration $c < 0.1$ ppt, Miraflores Lake: volume-averaged salt concentration c = about 0.7 ppt in the wet season and up to about 1.5 ppt in the dry season). The approximate range of volume averaged salinity values of other basins of the canal system, shown in Table 3.4, was also taken into account.

Many cases were built with variable duration. In these cases the exchange coeffcicients were further tuned. In particular the selection of the exchange coefficients used in the water-release scenarios was of importance.

The main conclusions of the validation runs are:

- With the selected exchange coefficients the simulation model is able to reliably predict the levels and seasonal variations of the salt concentration of Miraflores Lake and Gatun Lake.
- The volume-averaged salt concentration of Miraflores Lake varies between 0.7 – 1.5 ppt in dependence of seasonal influences: (i) variation of salt concentration and temperature of the water in the Pacific tailbays, (ii) lesser water releases in the dry season. The salt concentration of Gatun Lake varies similarly, mainly because of the lesser water releases in the dry season. The volume-averaged salt concentration of Gatun Lake is small and remains below 0.03 ppt, far below the fresh-water limit value of about 0.45 ppt salinity. (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)). Local salt concentrations in the lakes can be higher than the computed volume-averaged salt concentrations.
- The large tidal variation at the Pacific side causes a relatively small variation of the salt concentration in Miraflores Lake in particular, but is in the long run not of importance for the salt concentration level in the lakes.
- At present more salt intrudes Gatun Lake through Gatun Locks than through Pedro Miguel Locks and Gaillard Cut.
- Under the present meteorological and hydrological conditions, with the present ship-transit intensities and ship dimensions, and with the present water management of Gatun Lake and Miraflores Lake, stable salt concentrations in the lakes are obtained after a period of only 2 years (starting from zero salinity in the lakes).

1 Introduction

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

The available water resources for Canal operations have been analysed by the Canal Capacity Projects Division and several new water supply projects with potential for providing water for long-term Canal operation demands (including new locks) and for increased municipal and industrial needs have been identified. The Canal Capacity Projects Division has 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 A 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 in wet and dry season, the development of a 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 (Appendix III).

The combined Reports B, C and D present an analysis of the expected salt water intrusion for three-lift, two-lift and single-lift configurations of proposed Post-Panamax locks.

2 Review of data of existing situation

In this section we present the results of the review of the present canal system and canal operation. We review also data on salt water intrusion, and give an initial qualitative interpretation of the salt water intrusion through the locks on the Panama Canal.

2.1 Fact finding mission

2.1.1 Programme

In week 45, 2001, staff of WL | Delft Hydraulics has made a reconnaissance trip to Panama. The trip started with a kick-off meeting at the ACP offices in Balboa on 6 November 2001. Next to this meeting a fact finding tour was made that was led by ACP staff. This tour consisted of visits to the locks at the Pacific and the Atlantic side of the canal and possible sites for the construction of proposed Post-Panamax locks. With staff of ACP the lay out of the existing locks and the operation of the canal system were discussed. Discussions were also on the operational needs for salinity measurements in the locks, the lakes and the sea entrances. A visit was paid to Gamboa for inspection and selection of suited boats for the execution of the salinity measurements. Data and reports were collected on canal and lock operation, hydraulic conditions and previous studies on salinity intrusion.
The programme of the reconnaissance trip to Panama was as follows:

Tuesday 6 November 2001

Morning: kick-off meeting in the offices of the Canal Capacity Projects Division of ACP, Balboa; introduction to ACP staff; presentation of ACP on future canal expansion plans; presentation of ACP on the scope of work under the contract for the Salt Water Intrusion Study, presentation of WL | Delft Hydraulics on Detailed Project Work Plan and Schedule and Quality Assurance and Control Plan for the work under the contract (note: both plans are taken up in Appendix A).

Afternoon: visit to Miraflores Locks and surroundings

Wednesday 7 November 2001

Morning: boat trip to Gatun Locks for visit of locks and surroundings, and alignment A1 of new locks

Afternoon: back to Gamboa and visit to Pedro Miguel Locks and surroundings

Thursday 8 November 2001

Morning: visit to 'Instituto Geográfica Nacional Tommy Guardia' for collection of topographic maps
visit to port of Gamboa for inspection and selection of launches suited for measurements

Afternoon: concluding meeting in ACP office, Balboa

2.1.2 Collected data

During the fact finding mission and afterwards by (electronic) mail the next data were supplied by ACP:

Reports

Copy of Appendix B: 'Intermediate gates in the locks' from:
Isthmian Canal Commission (1910)
'Annual report of the Isthmian Canal Commission for the fiscal year ending June 30, 1910'
Government Printing Office, Washington, 1910

G.W. Goethals ed. (1916)
'The Panama Canal, an engineering treatise'
A series of papers presented at the Int. Engineering Congress, San Francisco, California, September 1915
McGraw-Hill Book Company, 1916
Copy of paper no 6 'Municipal engineering and domestic water supply in the canal zone', G.M. Wells
Copy of paper no 14 'General design of the locks, dams and regulating works of the Panama canal', H.F. Hodges
Copy of paper no 19 'Hydraulics of the locks of the Panama Canal', R.H. Whitehead

J.C. French, M.J. Webster (1942)
'The Panama Canal, The Third Locks Project, Lock model tests – design 3'
Department of Operation and Maintenance, August 1942

M.L. Jones, C.E. Dawson (1973)
'Salinity-temperature profiles in the Panama Canal'
Marine Biology, 21, pp 86 –90, 1973

A. Gonzalez S., G. Alvarado-Durfee, C.T. Diaz Z. (1975)
'Canal Zone Water Quality Study'
Panama Canal Company, Water and Laboratories Branch, Maintenance Division, June 1975

Panama Canal Commission, Marine Bureau (1988)
'Handbook of lockage procedure, Locks Division'
Revised Edition, 1988

R.A. Povirk, R.D. Rush (1999)
'Measurement of pressures related to vessel movement within Miraflores upper west lock'
US Army Corps of Engineers, June 30, 1999

T.M. Parchure, S.C. Wilhelms, S. Sarruff, W.H. McAnally (2000)
'Salinity Intrusion in the Panama Canal'
US Army Corps of Engineers, ERDC, February 2000

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

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

Moffatt & Nichol Engineers, INCA Engineers, Golder Associates (2001)
'Study of locks water-saving basins'
Draft final report, Vol 1, 2001.

Drawings

General map of the lands and waters of the Panama Canal
Cross sections and plans of Gatun Locks
Cross sections and plans of Miraflores Locks
Cross sections and plans of Pedro Miguel Locks
Hydrographic Survey maps of Panama Canal (scale 1:2500)
Alineamiento P1 y P2, Sector Pacifico
Alineamiento A1 y A2, Sector Atlantico
Panama Canal Elevations Diagram
The Panama Canal Clearance Diagram
Map of Pacific Entrance

Graphs and tables

Nivel de los Lagos y Usos del Agua (Lago Alhajuela y Lago Gatun, years 1990 – 2000
Table of ship transfers in the fiscal year October 2000 – September 2001

Digital data

Measurements of tide, Coco Solo Station, Atlantic Side, 1989 - 2000
Measurements of tide, Diablo Heights Station, Pacific Side, 1991 – 1999
Alignments A1 and A2, Atlantic Side
Alignments P1 and P2, Pacific Side
Geographic maps of Panama Canal
Some salinity measurements in Gatun Locks, Mirfalores Locks, Gatun Lake, Culebra
Gatun Lake, water level – water volume relationship
Gatun Lake, data on water level, water use for hydropower, spillage of water through Gatun Spillway
Miraflores Lake, data on maximum water level
Miraflores lake, data on mean water level and spillage of water through Miraflores Spillway
Ship transfers in fiscal year 2000 - 2001

Powerpoint presentations

'Water pressure measurements in the lock chambers', August 1999
'Planning a waterway for the future', 1999
'Shiplift alternative studies', December 1999
'Una Propuesta para la Ampliación del Canal', October 2000
'Capacidad del Canal Mayo', 2001
'St Lawrence Seaway', October 2001

Brochures

Various brochures on the Panama Canal, issued by ACP

2.2 Description of existing canal system and operation

2.2.1 General description

For the study of the salt water intrusion a thorough knowledge and understanding of the existing canal and lock system and the operation of the system is of vital importance. To that aim we have reviewed the design report of the Panama Canal [Vol 11, 1916, ed. G.W. Goethals], drawings of the locks, the operation manual, the relevant hydraulic conditions and ship transfer data. The results of the review are presented in brief outline in next sections.

The Panama Canal, in operation since August 1914, connects the Atlantic Ocean in the north-west with the Pacific Ocean in the south-east. The total length from ocean to ocean is about 80 km. Gatun Lake in the north-western canal area and Gaillard Cut, a narrow channel excavated in the rocks of the Continental Divide, form the highest part of the canal system. Gatun Lake is connected with the Atlantic Ocean by means of a double, three-lift lock system (two shipping lanes, Photograph 1). A double, single-lift lock system connects Gaillard Cut with the relatively small Miraflores Lake in the south-eastern canal area and a double, two-lift lock system connects Miraflores Lake with the Pacific Ocean.

Gatun Lake arose after construction of Gatun Dam in the lower reach of Chagres River, near the Atlantic Coast. Madden Dam was constructed in the upper reach of Chagres River and formed Alhajuela Lake (or Madden Lake); this second lake with mean water level of about +70 m (+230 ft) above PLD (Precise Level Datum), is an additional water reservoir for the Panama Canal. The mean water level of Gatun Lake is about +25.9 m (+85.0 ft); the corresponding water volume is 5.17 km^3. The water level of the lake fluctuates in dependence of either dry or wet season (wet season: mid May – December). The maximum variation is about 2.8 m (9.2 ft). 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 when a water level of about +26.7 m (+87.5 ft) is exceeded).
The water level variation of Gatun Lake throughout the year is shown in Figure 2.1 for the period 1992 - 2001. The lowest water level recorded in this period is +23.9 m (+78.4 ft).

The mean water level difference between Gatun Lake and Pacific Ocean is 25.6 m (84.0 ft), between Gatun Lake and Atlantic Ocean 25.85 m (84.8 ft)

The spillway in Gatun Dam, designed on a maximum discharge of 4955 m^3/s, has a circular plan form. The crest of the overflow spillway is at an elevation of +21.0 m (+69.0 ft); lifting gates close off the 14 bays, when the spillway is not in use. The rip-rap protected bed at the upstream side of the spillway was constructed at an elevation of +3.0 m (+10 ft); the local water depth amounted originally to 23.7 m (77.8 ft) at mean water level, but due to siltation the local water depth may be smaller nowadays. The six circular intakes of the hydropower plant with diameter of 3.2 m (10.5 ft) each, are at an elevation of +20.8 m (+68.25 ft), centre line.

The construction of the locks and dam at Miraflores has resulted in the formation of a small lake, Miraflores Lake. A few streams discharge into the lake, but their total discharge is only small, even in the rainy season. Miraflores Lake receives water from Gatun Lake through the lockages at Pedro Miguel. It looses water through the lockages at Miraflores, evapotranspiration, industrial water use, ground water flow and spillage of water through Miraflores Spillway. This spillway has been constructed in the dam beside Miraflores Locks.

At present the water level in Miraflores Lake is maintained at about +16.6 m (+54.4 ft), 0.25 m higher than in the years up to 1965, see Figure 2.2 (this figure shows the mean, minimum and maximum water level in a year in the period 1915 – 2001; the presented water levels concern averaged monthly values; the maximum value in a year is about 0.3 m higher than the mean value). A higher water level than +16.6 m (+54.4 ft) is not desired in view of the maximum allowed water level in the upper Miraflores Locks.

The water level in Miraflores Lake is controled by Miraflores Spillway. This spillway is straight in plan and designed on a maximum discharge of 2600 m^3/s. The relatively high design discharge was chosen for the purpose of discharging flood water in the case of failure of the Pedro Miguel Locks (which would lead to release of the water stored in Gatun Lake). The crest of the overflow spillway is at an elevation of +11.8 m (+38.67 ft); the 8 bays are closed off by lifting gates. The bed elevation at the upstream side was originally below PLD (= 0.0 m). The local water depth in the case of mean water level in the lake was thus greater than 16.6 m, but our salinity measurements near Miraflores Spillway indicate a water depth at present that is much smaller than that value, namely only 8 m.

The Pacific Ocean is shallow near the Panamanean coast. The entrance to the Panama Canal is excavated and requires a regular dredging maintenance. The so-called Amador Causeway, a dam between small islands near the coast and the shore, screens the entrance from currents and waves. The tide variation at the Pacific side is relatively strong (sea levels range between the extremes -3.44 m (-11.3 ft) and +3.60 m (+11.8 ft); mean sea level is +0.30 m (+1.0 ft)); as a result strong tidal currents occur in the full entrance up to Miraflores Locks.
The Atlantic Entrance to the Panama Canal is well protected against waves by breakwaters. The tide variation at the Atlantic side is small compared to the tide variation at the Pacific side (the tide varies between the extremes -0.38 m (-1.25 ft) and +0.56 m (+1.85 ft); mean sea level is +0.06 m (+0.20 ft)).

2.2.2 Locks

The locks on the Panama Canal have been designed for ships that require lock chamber dimensions of 1000 ft (305 m) length, 110 ft (33.5 m) width and 40 ft (12.2 m) water depth in salt water (41.7 ft (12.7 m) in fresh water). The layout of all locks is more or less similar. In the present study the locks are named A, B and C at the Pacific side and D, E and F at the Atlantic side, see the scheme of Figure 2.3.
Locks F (west and east lane), the upper locks at the Atlantic side which connect to Gatun Lake, have a double set of gates, both at the upstream and downstream end of the lock chambers (see Figure 2.4). The same holds for Locks C, which connect to Gaillard Cut, and Locks B, which connect to Miraflores Lake. These double set of gates are provided for safety reasons. Guard gates with their faces to the sea, are provided at the sea side of Locks D (Photograph 3) and Locks A.

The nominal head of the locks (head with reference to nominal, mean water level in lakes and sea entrances, and high / low water in locks) is shown in Table 2.1.

	nominal, mean water level					
	(ft to PLD)			(m to PLD)		
basin	high	low	lift	high	low	lift
Gatun Lake	+85.0		-	+25.91		-
lock C	+85.0	+54.0	31.0	+25.91	+16.46	9.45
Miraflores Lake	+54.0			+16.46		
lock B	+54.0	+26.0	28.0	+16.46	+7.92	8.53
lock A	+26.0	+1.0	25.0	+7.92	+0.30	7.62
Pacific Ocean	+1.0		-	+0.30		-

	nominal, mean water level					
	(ft to PLD)			(m to PLD)		
basin	high	low	lift	high	low	lift
Gatun Lake	+85.0		-	+25.91		-
lock F	+85.0	+57.0	28.0	+25.91	+17.38	8.53
lock E	+57.0	+28.0	29.0	+17.38	+8.54	8.84
lock D	+28.0	+0.2	27.8	+8.54	+0.06	8.48
Atlantic Ocean	+0.2		-	+0.06		-

Table 2.1 Nominal water levels in locks and lakes

The characteristic dimensions of the lock chambers are presented in Table 2.2. 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), the maximum length is the size between upper safety gate and lower gate. The normal chamber length is the size between upper gate and lower (safety) gate; this size corresponds to the minimum chamber length. The normal length is the gross length available for vessels in the lock chamber. Note that safety gates are at the upstream side of the normal gates; safety gates and normal gates are simultaneously used.
Floor level corresponds to the deepest part of the lock chambers; the sills which support the steel miter gates when they are closed, 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, facilitating a better

circulation of water under the ship hull and space for small obstacles which may fall into the chamber. Coping level corresponds to the top of the chamber walls.
The normal upper gates in Locks B, C and F which are located at the downstream side of the upper safety gates, are placed at the low side of the step in the floor; the upper safety gates are placed at the high side of the step (the usual position); the upper gates are thus as tall as the gates at the downstream side of these Locks B, C and F.

basin	*nominal length ft / m*	*maximum length ft / m*	*normal, mimimum length ft / m*	*width ft / m*	*floor level ft / m to PLD*	*sill level ft / m to PLD*	*coping level ft / m to PLD*
Pacific side							
A-west & A-east	**1080 ft** **329.2 m**	1161 ft 353.9 m	1080 ft 329.2 m	110 ft 33.5 m	-51.00 ft -15.54 m	-50.00 ft -15.24 m	+32.00 ft +9.75 m
B-west & B-east	**1089.5 ft** **332.1 m**	1181 ft 360.0 m	1008.5 ft 307.4 m	110 ft 33.5 m	-20.33 ft -6.20 m	-18.33 ft -5.59 m	+58.67 ft +17.88 m
Forebay B-west & B-east					+11.00 ft near intake +3.35 m	+11.33 ft +3.45 m	
Tailbay C-west & C-east					+8.50ft near outlet +2.59 m	+13.00 ft +3.96 m	
C-west & C-east	**1089.5 ft** **332.1 m**	1181 ft 360.0 m	1008.5 ft 307.4 m	110 ft 33.5 m	+11.00 ft +3.35 m	+13.00 ft +3.96 m	+92.00 ft +28.04 m
Forebay C-west & C-east					+37.33 ft near intake +11.38 m	+37.33 ft +11.38 m	
Atlantic side							
D-west & D-east	**1080 ft** **329.2 m**	1080 ft 329.2 m	1080 ft 329.2 m	110 ft 33.5 m	-44.33 ft -13.51 m	-42.33 ft -12.90 m	+34.67 ft +10.57 m
E-west & E-east	**1080 ft** **329.2 m**	1161 ft 353.9 m	1080 ft 329.2 m	110 ft 33.5 m	-15.33 ft -4.67 m	-13.58 ft -4.14 m	+64.25 ft +19.58 m
F-west & F-east	**1089.5 ft** **332.1 m**	1181 ft 360.0 m	1008.5 ft 307.4 m	110 ft 33.5 m	+13.67 ft +4.17 m	+15.00 ft +4.57 m	+92.00 ft +28.04 m
Forebay F-west & F-east					+14.0 ft near intake +4.27 m	+37.33 ft +11.38 m	

Table 2.2 Lock dimensions

The space between upper safety gate and upper gate (Locks B, C and F) is connected with the upper pool and the lock chamber by means of separate culverts. These culverts can be closed off with valves. The space between the gates can thus be a part of the upper pool or the lock chamber. Either of the two upper gates may therefore be used in locking. Normal

operation procedure is that both gates are simultaneously used and that the water in the space between the gates is not levelled down.
The space between the lower safety gate and lower gate (Locks B, C and F) is connected with the lock chamber at the upstream side of the gates by means of a culvert (in T-form) under the lock floor, which connects to the side wall culvert. This T-culvert can only be closed with the assistance of a crane. Normal operation procedure is that the lower safety gate and the lower gate are used simultaneously and that the water in the space is in open connection with the lock chamber. Consequently, this water is levelled down during a lockage.
Each lock (except of Locks A) is provided with a set of intermediate gates at about 1/3 of the lock length. These gates were designed for the purpose of saving water in case of a shortage of water in the dry period; they can be used when the vessel length is sufficiently small. In normal practise these intermediate gates are not utilized (at present most ships are too long).

The locks are provided with a floor filling system; many fill openings are applied in the lock chamber floors in order to equally distribute the inflowing water and to limit hindrance for ships.
Both the centre wall and the side walls are provided with a longitudinal culvert running the entire length of the lock flight and connecting the upper and lower pool. The centre wall culvert and the side wall culverts draw water from the upper pool through three rectangular openings. These openings can be closed by lifting valves. The centre wall culvert is horse-shoe shaped in cross section (sectional area 23.7 m^2 (255 ft^2)), the side wall culverts have a circular cross section (diameter 5.5 m , sectional area 23.7 m^2 (18.0 ft, 255 ft^2)). Lifting valves are provided in the main culverts at each lock lift. The centre wall culvert discharges through three openings in the centre wall. The side wall culverts are turned upward at the lower end and discharge through an opening that lays in a horizontal plane; this opening is situated in a recess in the side walls. The outflow is in upward direction and than spreads across the width of the forebay. An exception is the outlet in the side walls of Pedro Miguel Locks (Locks C): the lower end of the culverts is straight and the opening is in a vertical plain.
From the side wall and centre wall culverts lateral culverts with elliptical cross section of 3.8 m^2 (41 ft^2) branch off alternately into the floor of the lock chambers at a mutual distance of 11 m (36 ft). The side wall culverts are in open connection with the lateral culverts. Cylindrical vertical lifting valves have been installed between the centre wall culvert and the lateral culverts to either west and east lock chambers. The lateral culverts discharge upward into the lock chambers through filling openings, spaced uniformly across the chamber width. Each lateral culvert has five openings with diameter of 1.2 m (3.95 ft) and rounded edges. The locks have neither special provisions to prevent salt water intrusion nor water saving basins.

2.2.3 Operation of locks

The locks on the Panama Canal are 24 hours per day in operation. The theoretical maximum capacity is about 25 ship transits per lane (sum of both directions), 50 ship transits in total. The locks in the west and east shipping lane are independently operated, but normally the sailing direction of the vessels is the same in the two lanes. Early in the morning both lanes start with uplockages, followed by downlockages at about noon. Later on during the day the sailing direction is again changed from downlockage to uplockage and during the night from

uplockage to downlocakge. For safety reasons big vessels pass the narrow Gaillard Cut in the day time. The biggest vessels, the so-called Panamax vessels, require single lane in the Gaillard Cut and sail in semi-convoy. All lockages are programmed by the Marine Traffic Control (MTC).

A number of 50 ships transits per day implies 50 lockages at either side of the canal at an average time interval of 29 minutes.
In practice a ship lockage in the three-lift Gatun Locks takes between about 1.5 and 2 hours, depending on size and type of the ship, lockage procedure and safety measures. This lockage time is the total time between the moment that the ship crosses a line upstream of the locks and the moment it crosses a line downstream of the locks, or reverse (both lines perpendicular to the outer end of the approach wall). The lockage frequency, however, is higher because a second ship enters already the first lock when the first ship enters the third lock, and because smaller ships are locked in tandem (two ships in a lock chamber at a time in case that the sum of the lengths of the ships is smaller than 800 ft (244 m)).
A ship lockage in the two-lift Miraflores Locks takes between about 1 and 2 hours. Since the single-lift Pedro Miguel Locks and Miraflores Locks are simultaneously used the total effective period per day that the locks at the Pacific side are in operation, is less than at the Atlantic side. Consequently, there are waiting periods between turn arounds (change of sailing direction) at the Pacific side.

Normal lockage procedure is that the upper and lower safety gates of the upper locks of Gatun and Miraflores Locks (Locks F and B) and Pedro Miguel Locks (Locks C) are used together with the normal upper and lower gates. The nominal length (see Table 2.2) is the determinative size for the quantity of spilled lockage water. The upper locks are filled with water from the upper pool, lower locks are filled with water from the adjacent upstream lock in the same lane. Cross filling between locks in west and east lanes is not practised (apart from some limited water exchange in special cases). At Pedro Miguel Locks and Gatun Locks extra water may be supplied behind big vessels (beam > 99 ft (30.2 m), draught > 37 ft (11.3 m) in fresh water) in the case of downlockage; this water helps the vessel to sail out of the lock chamber This procedure is called the 'hydraulic assist procedure'. The extra water is drawn from the upper pool (Gaillard Cut or Gatun Lake).

To fill a lock chamber the gates in the main culverts in side wall and / or centre wall just upstream of the chamber are opened as well as the cylindrical valves in the centre wall (which free the openings to the lateral culverts, which branch off from the centre wall culvert). Gates are opened in about 1 minute. When both main culverts are used (double culvert lockage) it takes about 7.5 – 8 minutes to fill the upper locks of Gatun and Miraflores Locks and the single lock of Pedro Miguel Locks. It takes 6.5 – 7 minutes to equalize consecutive locks of a flight (the initial water-level difference is twice as big). It takes 7.5 – 8.5 minutes to empty the lower lock of a flight (depending also on the actual ocean level), and it takes 7.5 – 8 minutes to empty the single lock of Pedro Miguel Locks. A special procedure is 'double culvert lockage, slow fill' for ships with draft > 30 ft (9.14 m) and / or keel clearance at the sill < 10 ft (3.05 m). In this procedure only one of two gates of each of the main culverts is opened. When the water level has risen 10 ft (3.05 m), the second gate of both main culverts is opened.
When only the side wall culvert is used (single culvert lockage) the above mentioned intervals become about 13.5 minutes, 12.5 minutes 17.5 minutes and 15 minutes, respectively.

Visual observations show that the inflow of water is reasonable uniform over the area of the lock chamber. When only one main culvert is used it is noticed that initially the greatest discharge comes from those openings in the lateral culverts which are farthest from the main culvert in use. In the case of uplockage (ship in the lock chamber) this phenomenon is the cause that the ship tends to move to the side with main culvert in use. Emptying the lock chamber in the single culvert lockage mode does not cause problems for the ship in the lock chamber.
Restrictions are imposed on lock operations when the water level in Gatun Lake falls below a level of +81.5 ft (+24.85 m), both in view of the smaller water depth in the lock chambers and saving of spill water.

2.2.4 Ship transfers

Vessels enter and leave the lock chambers with the help of electric locomotives (Photograph 2); they are driven by pushtows (Photograph 7) or use their own engines. Their normal speed is 3 miles / hour, but depending on type and size of the ship smaller speeds are practised. Hawsers are connected through winches to the locomotives, which run on rail at both sides of the locks. The locomotives function as moving mooring posts. They keep the vessel in the centre of the lock chamber during sailing and during filling and emptying (ships are not allowed to use thrusters) and may also assist in towing and braking of the vessel. The total number of locomotives per vessel varies between 4 and 8, the total number of hawser cables between 4 and 16, depending on length, beam and tonnage of the vessel.
Locomotives use only one track. As a consequence, when a number of ships has locked up or locked down, locomotives concentrate at one side of the lock complex. A special relay procedure is designed to return the locomotives to their start position. In this procedure the vessel in the lock chamber is tight up to fixed bollards, locomotives pass the ship and the last locomotives take over the vessel.
Various types of vessels pass the Panama Canal. Most of them have a beam greater than 80 ft (24.4 m) and a PCUMS net tonnage greater than 15,000. In Table 2.3 vessels that passed the canal in the fiscal year October 2000 – September 2001 are grouped in vessel type and net tonnage.

Vessel type	*Number of transits*	*Percentage of total transits*	*Average PCUMS net tonnage*
Bulk carriers	3,704	23.36	25,927
Container cargo	2,365	14.91	28,326
Container / break-bulk ship	407	2.57	17,066
Roll-on roll-off ships	178	1.12	26,090
Full container ships	1,780	11.23	31,123
General cargo	1,119	7.06	7,644
Passenger ships	236	1.49	35,257
Refrigerated cargo	2,560	16.14	6,320
Tankers	1,850	11.67	16,553
Liquid gas carriers	208	1.31	12,959
Other	1,450	9.14	1,248
Total	15,857	100.00	

Table 2.3 Ship transits in fiscal year October 2000 – September 2001

The total number of 15857 transits in 2001 means an average number of 43.4 transits per day. The average number of ocean-going vessels is 34.3 per day.
When a distinction is made in ship beam and net tonnage the Table 2.4 is obtained:

The biggest vessels that pass the Panama Canal ('Panamax vessels') have the following dimensions: length 965 ft (294 m), beam 106 ft (32.3 m) and draught 39.5 ft (12.0 m, in tropical fresh water).

Beam class	*Number of transits*	*Percentage of total transits*	*Total net tonnage per class*	*Percentage of total net tonnage*	*Average net tonnage per class*
< 80 ft (< 24.4 m)	6,744	42.53	37,098,230	12.44	5,501
80 – 100 ft (24.4 - 30.5m)	3,258	20.55	60,403,510	20.26	18,540
> 100 ft (> 30.5 m)	5,855	36.92	200,657,419	67.30	34,271
Total	15,857	100.00	298,159,159	100.00	18,803

Table 2.4 Ship transits in fiscal year October 2000 – September 2001, beam classes

2.3 Review of salinity reports and data

In this section emphasis is put on previous salinity measurements and studies. The operation of the locks, the hydraulic conditions and ship transits have been discussed in Section 2.2. For a definition of *salinity* and *cloridity* reference is made to Section 3.2.5.

Drinking water intakes in relation to salinity (Goethals (ed.), 1916)

The construction of the dam and locks at Miraflores in the period up to 1914 necessitated the design of a new drinking water intake for Panama City. The project as first recommended and adopted involved the taking in of raw water from one of the eastern arms of the newly created Miraflores Lake. It was already recognized that the chlorine content (a measure for the salinity of the water) of the lake would rise after the locks were opened for traffic. It was therefore that only temporary pumps were installed near the proposed permanent station.
By May 1914 the chlorine content had risen to 0.15 per mille at the bottom and to 0.1 per mille at the surface throughout Miraflores Lake. It was then decided to move the intake to the present location near Gamboa, i.e. the location where the Chagres River enters Gatun Lake. The raw water that is drawn from this location, is regularly sampled and analyzed. Relevant chlorine concentrations are not found.
The drinking water intakes of Colon at the Atlantic side draw their water from the Brazos Brook reservoir, which is connected to Gatun Lake.

Salinity measurements (Jones and Dawson, 1973)

Jones and Dawson made a study on the assumption that the Gatun Lake acts as a fresh water barrier to the migration of marine animals from either end of the canal to the other. To that aim a series of salinity-temperature profiles were taken in all locks on the Panama Canal and adjacent waters. Measurements were executed with the help of a Beckman portable salinometer, both in April and in November 1972. The results are presented in the above paper together with results of earlier measurements by Hildebrand (1939), Menzics (1968), and Bozniak (1969).

Hildebrand found from hydrometer readings:
Surface salinity: 16 – 20 per mille in the Pacific Entrance, 0.1 – 3.0 per mille in Miraflores Lake, 0.005 – 0.020 per mille in Gatun Lake and 18 – 20 per mille in the Atlantic Entrance.

Menzics found from towing experiments (no information on season, type of measurements and depth of measurements):
Salinity: Pacific Entrance 30 per mille, in one of the Miraflores Locks 25.5 per mille, Miraflores Lake 1.0 per mille, 0.0 per mille in Pedro Miguel Locks, 0.0 per mille in Gatun Lake, 23.5 per mille in one of the Gatun Locks, and 28.5 per mille at Coco Solo, in Limón Bay, on the Atlantic side.

Bozniak found for salinities in the Miraflores Third Locks Lake, a narrow excavation near the Miraflores Locks, that is subject to salt water incursions from the Bay of Panamá during high tides, values of 10 per mille near the surface and 22.6 per mille near the bottom at the deepest part. The Third Locks Lake is not in open connection with Miraflores Lake.

The measurements of Jones and Dawson show essentially:

- fresh water to be present from Miraflores Lake through Pedro Miguel Locks, through Gatun Lake, to and including the upper chambers of Gatun Locks,
- vertical profiles to indicate homogeneity and thorough vertical mixing of all water masses in the lock systems and lakes (with the exception of the lower locks of Miraflores), but not necessarily horizontal homogeneity; density driven exchange flows were also observed during opening of the gates, indicating the existance of a layered system,
- water in the Pacific approach channel to be more homogeneous than in the Atlantic approach channel,
- seasonal differences to be present: lower salinities following the wet season and lower temperatures during the Pacific upwelling of the dry season.

Canal Zone Water Quality Study (Gonzalez et al, 1975)

Early seventies the Panama Canal Company has executed a water quality study project. Measurements were undertaken on the existing physical, chemical and biological parameters of the marine and fresh water areas of the Canal Zone and their relevancy thoroughly studied, while also the effects of domestic and industrial waste water effluents on the water quality was studied.

The study revealed the following data on *cloridity* levels (in per mille or ppt):

Miraflores Lake:

	Near water surface			*Near bed*		
Season	maximum (ppt)	minimum (ppt)	mean (ppt)	maximum (ppt)	minimum (ppt)	mean (ppt)
Dry season	0.63	0.39	0.51	1.02	0.43	0.66
Wet season	0.39	0.09	0.30	0.69	0.10	0.37

When the *cloridity* values are converted into *salinity* values (cloridity : salinity 3 : 5) one finds:

	Near water surface	*Near bed*
Season	mean (ppt)	mean (ppt)
Dry season	0.85	1.10
Wet season	0.50	0.62

Clearly, *salinity* levels in Miraflores Lake are higher in the dry season than in the wet season, and the highest *salinity* values are found near the bed of the lake.

Madden Lake, Gatun Lake, Gaillard Cut:
Cloridity levels in Madden Lake, Gatun Lake and Gaillard Cut were found to be in the range 4 – 9 ppm throughout the year. These values correspond to very low *salinity* values (< 0.02 ppt).

ACP measurements (1999)

The Environmental Management Division of ACP now and then executes salinity measurements (Hydrolab salino meter). The next data were made available for the present study:

Gatun Lake
Measurements on 5 May 1999 in stations numbered 1 – 30, east side, west side and centre of Gatun Lake, depths 0 ft, 20 ft and 40 ft. Observed salinity in all measurement points: 0 per mille.

Corte Culebra (Gaillard Cut)
Measurements on 6 May 1999 in stations numbered 1 – 25, east and west side of Gaillard Cut, depths 0 ft, 20 ft and 40 ft. Observed salinity in all measurement points: 0 per mille.

Miraflores Locks
Measurements on 21 October 1999 in centre line of locks A-east and B-east (no vessel in chamber where measurements take place).
Lock A-east, low level, three vertical salinity profiles in longitudinal direction of lock chamber:

depth (ft)	*begin of chamber (ppt)*	*mid section (ppt)*	*end of chamber (ppt)*
0	12.0	12.0	12.4
20	23.8	24.0	24.5
40	25.1	25.2	25.5
55	25.5	25.9	25.7

These measurements indicate some layering in the lock. During filling of the lock chamber with water drawn from the adjacent lock B the salinity was measured as function of time at a depth of 15 ft. The salinity reduced from 22.6 per mille to 18.4 per mille.

After filling salinity levels were again measured in lock A-east:

depth (ft)	*begin of chamber (ppt)*	*mid section (ppt)*	*end of chamber (ppt)*
0	16.9	16.6	16.7
20	17.2	17.5	17.8
40	17.4	17.9	-
55	18.0	18.7	19.1

The measurements show a more uniform salinity after filling with water from the higher lock B (indicating strong mixing during filling) and an overall reduction of the salinity.

The same procedure was followed for lock B-east, the upper lock of Miraflores.
Measurements on 21 October 1999
Lock B-east, low level, two vertical salinity profiles in longitudinal direction of lock chamber:

depth (ft)	*begin of chamber (ppt)*	*mid section (ppt)*
0	1.3	1.3
20	2.6	2.0
55	14.1	9.8

These measurements indicate lower salinity levels than in lock A-east, and an apparent layering in the lock. During filling of the lock chamber with water drawn from Miraflores Lake the salinity was again measured as function of time at a depth of 15 ft (4.6 m). The salinity varied between 2 - 3 per mille.

After filling salinity levels were again measured in lock B-east:

depth (ft)	*begin of chamber (ppt)*	*mid section (ppt)*	*end of chamber (ppt)*
0	2.8	1.8	1.8
20	3.0	2.2	2.2
55	3.1	2.9	2.7

The measurements show a rather uniform salinity after filling with water from Miraflores Lake (again indicating mixing during filling).

Salinity measurements in Gatun Locks were executed on 30 November 1999, indicating salinity levels between 0 and 5 per mille in the upper lock. Measurements near the sway bridge at the downstream side of the locks indicated salinity values between 10 per mille near the water surface and 33 per mille at a depth of 55 ft (16.7 m).

Salinity intrusion in the Panama Canal (Parchure et al, 2000)

A study was conducted by the Coastal and Hydraulics Laboratory of the US Army Engineer Research and Development Center (ERDC) in Vicksburg on salinity intrusion through the locks on the Panama Canal. The effect of an expansion of the canal locks capacity by means of a new shiplift at both sides of the canal was taken into account. The study identified also possible measures to reduce the salinity intrusion. Spreadsheet calculations were made for salt loading and water spillage caused by lockages and a two-dimensional (2DH) model was used to depict the dispersion path of salt water, if any, in the Gatun Lake. A literature review identified potential salinity mitigation methods (which are not discussed further in the present report).

In the above salinity intrusion analysis the subsequent steps in upward or downward lockage are separately treated. These steps are: (i) open gates, move ship into lock chamber, (ii) fill or empty lock chamber, (iii) open gates, move ship out of the lock chamber, and (iv) empty or fill lock chamber, back to step (i). In the analysis it is assumes that dissolved salt in the lock chamber is completely mixed at the end of each step and that the fill water has the same salt concentration as the water in the upstream basin where it is drawn from. When gates are opened between two basins a density driven exchange flow occurs and the ship's submerged volume is exchanged. A standard exchange coefficient of 0.5 is applied without making distinction between uplockage and downlockage, flat bottom or step in bottom. Some calibration of coefficients is done by matching computed salinity levels with observed field salinity levels (salinity Pacific Entrance 10 per mille, lower lock Miraflores 8 per mille, upper lock Miraflores 1.5 per mille, Miraflores Lake 1.0 per mille and Gatun Lake 0 per mille). Lake levels and ocean levels are assumed to be constant in time. This approach leads to a steady state salt concentration of 0.03 per mille in Gatun Lake after a period of 5 years. With the Syncrolift locks the steady state concentration in Gatun Lake rises considerably.

Major shortcoming in this analysis is the lack of reliable salinity data for the determination of exchange coefficients, no distinction between uplockage and downlockage, flat floor or step in floor and ship dimensions. The method itself is basically sound.

Conclusions

The main conclusions that can be drawn from these salinity data studies are:

- The salt concentration in Gatun Lake is almost negligable (salinity levels < 0.2 ppt throughout the year); Miraflores Lake has a low salt concentration (salinity levels are up to 3 ppt, in particular near the bed of the lake; salinity values are higher in the dry season than in the wet season).
- Salt concentrations in the Atlantic and Pacific Entrances are lower than salt concentrations in the oceans, in particular near the water surface near the locks.

- The floor filling system in the locks facilitates a good mixing of fill water with the water in the lock, resulting in a rather uniform salt concentration; mixing is sustained by the propellor action of the sailing ship.
- Density currents and layering occur in the locks when the gates are opened.

2.4 Initial qualitative interpretation of salt water intrusion process

Salinity measurements which were undertaken in the past (see Section 2.3) indicate that lockage operations cause salt water intrusion in Miraflores Lake (two water level steps from Pacific Entrance to Miraflores Lake) and almost no salt water intrusion in Gatun Lake (three water level steps from the Pacific and Atlantic Entrances to Gatun Lake).

The exchange of water during lockage of a vessel is a rather complex process. Several stages of operation can be discerned in the locking process:

- Lock gates are open at one side of the lock chamber. Density differences between the water in the lock chamber and the water outside cause an exchange of water. The velocity of a salt water tongue entering the basin with lower density can be relatively high (several tens of centimeters per second). The exchange of water is clearly a function of the density difference and the time that the lock chamber is open, but is also influenced by the geometry of the lock chamber (step in floor or flat floor) and the position and dimensions of the ship. Mixing may break up a layered situation and the salt penetration velocity may consequently decrease rapidly. Factors that influence mixing are ship movements, propellor action and wind.
- A vessel is entering or leaving the lock chamber. The movement of the ship causes a return current, which influences the density flows. Both surface waves, translatory waves and internal waves may occur and they reflect on the ends of the lock chamber. The strength of the return current is depending on factors such as the speed of the ship, the blockage ratio and the local geometry (step in floor or flat floor). A net quantity of water equal to the volume of the ship below the water surface is exchanged.
- Lock gates are closed and the water in the lock chamber is either levelled with the high basin or the low basin. In the case of the Panama Canal water basins with lowest density are at the high side. Consequently, fill water has a lower or equal density as the receiving water in the lock chamber. A filling system with openings in the floor of the lock chamber causes a relatively strong mixing. Mixing is depending on factors such as filling discharge, jet velocity, number and cross-sectional area of filling openings, location of openings, water depth and in the case of uplockage dimensions and position of the ship. When the openings in the floor are used to empty the lock chamber, water with highest density may first be discharged to the lower basin.

There are evident differences between uplockage and downlockage of ships. In the case of uplockage the ship is in the lock chamber that is filled with water from the higher adjacent basin. Initially the water volume in the lower lock is relatively small compared to the ship's submerged volume. The inflow of water through jets is influenced by the ship that floats above the fill openings. When the adjacent high basin is a lock, water is drawn from an initially large water volume (without ship), and initial inflow velocities in the jets may be high because of the initial great water level difference. When the adjacent high basin is a

lake, water is drawn from the area between the side wall and the centre wall, near the upstream gates. When the water levels in both basins have been equalized and the upstream gates are opened, the ship has to pass the step in the lock chamber floor (except when the low basin is the sea entrance or a lake). The keel clearance at the step is of importance for return currents and possible piston effects (water in the high lock may be set up).

In the case of downlockage the ship is in the lock chamber where the water is drawn to fill the low basin. When the low basin is a lock, the filling jets are not blocked by a ship and can freely expand. Initially the fill water with - most probably - a lower density widens and spreads near the water surface. Because many jets are present spreading is limited and fill water expands in upward and downward direction, the latter because of an intensive mixing due to the jet-generated turbulence. When the ship sails from the high basin to the low basin it passes a downward step (except when the low basin is the sea entrance or a lake). Again the keel clearance at the step is of importance for return currents and piston effects (the water level in the adjacent high lock may be drawn down).

The various steps in uplockage and downlockage can not fully be simulated in a three-dimensional numerical flow model. Instead, a simplified simulation model has to be applied in which exchange coefficients are used to quantify the exchanged water volumes between separate basins with different salinities. These exchange coefficients are, in general, different for the various steps in the lockage process and vary in dependence of several influencing factors.

3 Field-data collection salt water intrusion

3.1 Introduction

Field measurements were required to collect sufficient data for the study of salt water intrusion in the Panama Canal. The field-data collection programmes were such designed that, in particular, data were obtained for the analysis of the physical processes during uplockage and downlockage, while also data were collected for the determination of exchange coefficients for use in the numerical model, that simulates the process of salt water intrusion. In addition, present salinity levels in Gatun Lake and Miraflores Lake were measured as well as salinity levels in the sea entrances.
Panama has two seasons, the wet season from mid May to end of December and the dry season from January to mid of May. Since seasonal variations (variation of water level in Gatun Lake caused by seasonal variation of precipitation, variation of spillages from the lakes, seasonal upwelling of colder and more saline water at the Pacific Coast during the dry season) were regarded as possible influencing factors for the process of salt intrusion, measurements have been executed by the end of the wet season and the dry season.

Wet-season data collection

The wet-season data collection programme was set up after the reconnaissance mission to Panama in week 45, 2001, and prior to the execution of the measurements in weeks 48 – 50, 2001. The programme was presented to ACP staff at the meeting which was held on 27 November 2001 in the offices of the Canal Capacity Projects Division of ACP in Balboa. The full data collection programme is taken up in Appendix I of this report.

The aim of the measurements in the wet-season was:
- to get insight in the hydraulic processes which occur in the locks during operation, including water exchange porcesses when the lock gates are opened and ships move in and out, density flows, mixing of water during filling and emptying,
- to measure salinity levels and gradients in the approach harbours,
- to measure salinity levels and gradients in Miraflores Lake, Gaillard Cut and Gatun Lake.

Dry-season data collection

The dry-season data collection programme was set up after execution of the wet-season data collection programme, taking into account the insights and experiences which were obtained through the wet-season measurements. The dry-season data collection programme is shown in Appendix II.

The aim of the dry-season measurements was:
- to measure salinity levels in Miraflores Lake, Gaillard Cut and Gatun Lake and, by comparing with the previous measurements, to get insight in changes in salinity levels after a period of little rainfall,

- to broaden the insight in the hydraulic processes which occur in the locks during operation, by means of additional salinity measurements in forebays, tailbays and lock chambers,
- to fill up gaps in measurement data of the wet-season programme, in particular gaps in measurement data for locks at the Pacific side, both under low tide and high tide conditions,
- to collect additional data for the determination of exchange coefficients.

Contrary to the separate salinity measurements in the wet season, simultaneous measurements were planned and carried out in the dry season in two adjacent lock chambers, in lock chamber and forebay, and in lock chamber and tailbay. These simultaneous measurements were found to be necessary in view of a more reliable determination of exchange coefficients.

The dry-season programme was presented and discussed with ACP staff at the meeting, which was held on 9 April 2002 in the ACP premises in Balboa prior to execution of the programme. Execution took place in weeks 15 and 16, 2002.
Measurements were carried out by staff of WL | Delft Hydraulics with the assistance of staff of Sección de Control de Contaminación y Vegetación Acuática of ACP.

3.2 Method

3.2.1 Relevant phases in lock operation for salinity measurements

In lock operation two steps in particular can be distinguished, which are relevant for the salt water intrusion process. These steps are described here in brief, both for uplockage and downlockage.

Uplockage

Step I: equalize water level in low basin (with ship) with water level in high basin (without ship)
The low basin can either be a sea entrance, a lock, or a lake. In the case of a lake and a sea entrance the water level in the low basin remains the same and the high basin (lock) is levelled down.
The high basin can either be a lock or a lake. When low and high basin are locks the initial water level difference between the basins and initial jet flow velocities are highest. Fill water is drawn from the high basin. When the high basin is a lock water is drawn through distributed openings in the floor; when the high basin is a lake water is drawn through a few openings in the centre wall and / or side wall. Mixing in the low basin depends on inflow velocity, double or single-culvert lockage and ship dimensions.
Step I is finished when the gates between both basins are pushed open by the water in the low basin (in the case of a density difference between the basins the water level in the high basin being still a little above the water level in the low basin).

Step II: gates are opened and the ship moves from low basin to high basin
The low basin can either be a sea entrance, a lock or a lake. In the case of a sea entrance and a lake there is no upward step in the floor at the entrance to the high basin.
The high basin can either be a lock or a lake; there is a step in the floor at the entrance to the high basin.
When the gates between low and high basin are opened density-driven exchange flows occur. These flows depend on the density difference between the two basins, the local geometry, the position of the vessel, and the duration of gate opening. When the ship moves from low basin to high basin the ship's submerged volume is exchanged. The propellor of the ship causes mixing.
Step II is finished when the gates between both basins have been closed.

For practical reasons it was not possible to continuously measure the salinity levels and changes of salinity throughout the lock chambers during the full uplockage process. Measurements, therefore, were limited to a few phases of the lockage process. These phases are:

1. Measurement of salinity profiles in long sections in the lock chamber prior to entering of the ship.
2. Measurement of salinity profiles near the upstream gates when the ship moves in.
3. Measurement of salinity profiles near the downstream gates when the ship moves out.
4. Measurement of salinity profiles in long sections in the lock chamber after the ship has left and the gates are closed.
5. Measurement of salinity profiles in long sections in the lock chamber after the water has levelled down and prior to opening of the downstream gates.

The five different phases are shown in Figure 3.1.

Downlockage

Step I: equalize water level in low basin (without ship) with water level in high basin (with ship)
The high basin can either be a lake or a lock. In the case of a lake the water level in the high basin remains the same and the low basin (lock) is levelled up.
The low basin can either be a lake, a lock or a sea entrance. When high and low basin are locks the initial water level difference between the basins and initial jet flow velocities are highest.
Fill water is drawn from the high basin. When the high basin is a lake water is drawn through a few openings in the centre wall and / or side wall; when the high basin is a lock water is drawn through distributed openings in the floor; the ship is above these openings. Mixing in the low basin (without ship) depends on inflow velocity and double or single-culvert lockage.
Step I is finished when the gates between both basins are pushed open by the water in the low basin (in the case of a density difference between the basins the water level in the high basin being still a little above the water level in the low basin).

Step II: gates are opened and the ship moves from high basin to low basin
The high basin can either be a lake or a lock. The low basin can either be a lake, a lock or a sea entrance. In the case of a lake and a sea entrance there is no downward step in the floor at the entrance to the low basin.

When the gates between high and low basin are opened density-driven exchange flows occur. These flows depend on the density difference between the two basins, the local geometry, the position of the vessel, and the duration of gate opening. When the ship moves from basin to basin the ship's submerged volume is exchanged. The propellor of the ship causes mixing.
Step II is finished when the gates between both basins have been closed.

Similar as for uplockage, in practice salinity measurements in the lock chambers were limited to the next five phases:

1. Measurement of salinity profiles in long sections in the lock chamber prior to entering of the ship.
2. Measurement of salinity profiles near the downstream gates when the ship moves in.
3. Measurement of salinity profiles near the upstream gates when the ship moves out.
4. Measurement of salinity profiles in long sections in the lock chamber after the ship has left and the gates are closed.
5. Measurement of salinity profiles in long sections in the lock chamber after the water has levelled up and prior to opening of the upstream gates.

The five phases are shown in Figure 3.2. Photographs 4 – 6 give an impression of the execution of salinity measurements in the lock chambers.

Forebays and tailbays of locks

In addition to salinity measurements in the lock chambers salinity measurements have been carried out in the forebays and tailbays at the upstream and downstream side of the locks respectively. Measurements in the wet season were limited to periods without shipping (apart from the continuous measurements with a fixed CT logger on the nose of the centre wall, see Section 3.2.3). In the dry season attention was also focused on the salinity changes in the forebays and tailbays under the influence of water withdrawal, water spillage and ship movements. These measurements were usually executed in combination with measurements in the adjacent lock chamber. For practical reasons salinity measurements in forebays and tailbays were limited to the next three stages of the lockage process:

Uplockage, tailbay

a Measurement of the salinity of water that is spilled from a lock to the tailbay (measurements near outlet). The tailbay is either located in the Atlantic Entrance, the Pacific Entrance or in Miraflores Lake.
b Measurement of salinity profiles in a long section in the tailbay just after spilling and prior to opening of the lock gates and movement of the ship.
c Measurement of salinity profiles in a long section in the tailbay after passage of the ship and closure of the lock gates.

See Figure 3.3.

Uplockage, forebay

a Measurement of the salinity of water that is drawn from the forebay (measurements near intake). The forebay is either located in Gatun Lake, Gaillard Cut or in Miraflores Lake.
b Measurement of salinity profiles in a long section in the forebay just after taking in of water and prior to opening of the lock gates and movement of the ship.
c Measurement of salinity profiles in a long section in the forebay after passage of the ship and closure of the lock gates.

See Figure 3.3.

Downlockage, forebay and tailbay

Salinity measurements have been carried out in the forebays and tailbays of the locks. In the dry season, measurements were in particular focused on the effects of water movements and ship movements. Measurements were limited to three different phases during downlockage, similar as for uplockage, see Figure 3.4.

3.2.2 Salinity measurements in sea entrances and lakes

Salinity levels and gradients in the Atlantic and Pacific approach channels depend on tidal movements, geometry of the sea entrances, frequency and direction of ship movements and spillages related to uplockage and downlockage lock operations. At the same time, the actual water level and salt concentrations near the lower locks of Miraflores and Gatun are of importance for the salt water intrusion through the locks (water level and concentration in the sea entrances are variables in the salt water intrusion process). Salinity measurements in the sea entrances were, therefore, in particular focused on the area nearby the locks, but data on salinities has also been collected in the approach channels.

Salt water intrusion in Miraflores Lake, Gaillard Cut and Gatun Lake is caused by lock operations and is the net result of: (i) exchange of water 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 flow, evaporation) is nill or can be neglected in the analysis.
Salt water that enters the forebays of the locks through locking operations is partly sluiced back when the water in the lock chambers is levelled up, but may also spread into the entire lake area. The salinity level in the lakes may thus vary in dependence of the distance to the locks. The heavier, saltier, and possibly colder water will preferably follow a path along the bed. Flows towards the spillways caused by spillage of surplus water or usage for power generation may influence the direction and speed of the density currents. The saltier water may concentrate in the deeper parts of the lakes, but will also dilute and spread throughout the lakes.

The salinity level in the lakes is thus a function of inflow and outflow of water and distance to the locks and may vary during the year. For this reason measurements in the lakes were required both in the wet and dry season, in particular in the deeper shipping channels and berthing places and near the spillways in Gatun Dam and Miraflores Dam.
At the end of the dry season the water level of Gatun Lake and Gaillard Cut is lower than in the wet season and consequently the water and salt exchange processes at Pedro Miguel Locks and the upper locks of Gatun may be different in dry and wet season. This has put the water level in Gatun Lake and Gaillard Cut as a variable in the salinity measurements near the locks.

3.2.3 Method of salinity measasurements

Measurements of vertical salinity profiles in lock chambers, forebays, tailbays, lakes and sea entrances have been carried out with two, fast response CTD instruments (CTD = conductivity, temperature and depth below water surface). From these measurements both the salinity and the density can be derived as a function of depth below the water surface.
The two CTD's were deployed in the locks, the canal area and the sea entrances, using two small survey boats (launches Cara Cara and Perico, Photograph 5), which were made available by ACP. A third, CT-instrument connected to a data logger, was put into service to measure the salinity at a number of well chosen, fixed locations, in the forebays and tailbays of the locks, both at the Pacific side and the Atlantic side. Measurements with the CT-logger were done during a longer period of time, so as to get a picture of salinity variations in the tailbays and forebays caused by the tide, lock operation and ship movements.
Positioning outside the locks, forebays and tailbays was done with GPS, yielding a horizontal accuracy of typically 5 m. In the locks positioning was done using distance marks on the lock walls.
Together with the measurements other relevant data were collected, including wheather conditions, water levels, dimensions and type of ships in locks, and lock operation.
The work in the locks and channels was coordinated by ACP staff.

Considerations and decisions for the salinity measurements in tailbays, locks, forebays, and lakes were:

- Since east- and west lanes are simultaneously used in the same direction, locking processes in the two lanes are similar; consequently, the need to do salinity measurements in each of the two lanes did not exist. The choice of a lane (lock chamber / forebay / tailbay) was fully dependent on the actual ship traffic and possibilities to fit into the locking schedule.
- Small survey boats were regarded as the best and most efficient option to carry out salinity measurements with CTD instruments.
- Prelimenary ship transit schedules were prepared one day in advance by the Marine Traffic Control Department (MTC). In consultation with MTC possibilities to execute measurements were discussed and measurements were scheduled in the transit scheme for the next day.
- Balboa was selected as the home basis for measurements at the Pacific side, Colon as the home basis for measurements at the Atlantic side.
- Lodging and transport was organized and provided by ACP.

Measurements in the locks were planned taking into account limitations imposed by ship dimensions, classification of the ship's cargo, safety regulations and the demand for a

minimum of delay for shipping. For instance, for safety reasons it was not allowed to do measurements in the locks with the launches positioned at the upstream side of the vessel, unless the vessel was small enough to tie up the launches before the point where the lock walls have an incline to the level of the next lock.
Planned measurements were also not always possible because of changes in the ship transit schedule. In that case alternatives were discussed with MTC, sometimes resulting in the decision to do measurements at an other occasion, at an other day.

3.2.4 Description of transducers and data acquistion

The salinity profilings have been carried out with CTD-12 Plus instruments of Applied Microsystems Ltd. This type of instrument is a multi-parameter, self-contained, intelligent CTD, that is designed for the measurement of conductivity, temperature and pressure. The CTD-12 Plus features microprocessor based CMOS circuitry, a 4-1/2 digit analog digital converter (1 part in 40,000) and 128 Kbytes of battery backed-up random access memory (RAM) for data storage.

The CTD-12 Plus is designed to be used with an IBM compatible computer. The instrument's output is standard ASCCI-232, permitting data transfer via a 3-conductor cable. The baud rate is automatically selected with the maximum being 19,200. The data output may be configured to display either unprocessed integers, or computed engineering values. The CTD-12 Plus has the options of logging data continuously, by depth increments, by time increments or logging individual scans.

The aluminium pressure case and sensor protection cage are hard-anodized for corrosion resistance and durability. Nylon bumpers on each end of the instrument provide additional protection. All other external parts are type 316 stainless steel. The presusure case is submersible to 5000 metres of water depth (dependent also on installed pressure sensor).

The CTD-12 Plus has the following specifications:

Pressure:

Type:	Keller stainless steel pressure transducer
Range:	Assorted pressure ranges up to 5000 dBars
Accuracy:	0.15% of Full Scale
Resolution:	0.005% of Full Scale
Response time:	10 ms

Temperature:

Type:	Pressure protected precision aged thermistor
Range:	-2 °C to 32 °C
Accuracy:	±0.005 °C
Resolution:	0.001 °C
Response time:	100 ms

Conductivity (unit mS/cm = milliSiemens per cm):

Type:	Patented four platinized electrode cell
Range:	0.2 to 65 mS/cm in salt mode
	0.2 to 6.5 mS/cm in fresh mode

Lower limit: the lower measurement limit of 0.2 mS/cm corresponds to a salinity value of about 0.1 ‰ in water with a temperature of 28 °C; lower salinity values can not (reliable) be measured
Accuracy: ±0.01 mS/cm (measurement of salinity level better than 0.01 ‰)
Resolution: 0.003 mS/cm
Response time: 5-25 ms

Memory: 128k battery backed-up RAM, expandable to 40 MBytes. The standard RAM can record 8,400 data scans with 7 data channels. With 8 channels, the CTD-12 Plus can record 7400 individual scans.

Output: RS-232C 300 to 19200 baud, ASCCI, 8 data bits, no parity, 1 stop bit. The baud rate is automatically determined and selected.

Sample rate: When recording internally with sending data, the scan rate is selectable from 15 scans/second to one every 24 hours. The maximum scan rate decreases if additional sensors are mounted on the instrument. If a scan is chosen which is faster that the scan rate capacity of the instrument the instrument will default to its maximum scan rate.

Time Code: Real time clock
Accuracy: ± 1 minute/month at 25 °C

Power: Standard: 9 Alkaline D-Cells, 6 Amp-hours

The CT-logger that was used to measure the salinity at selected locations comprises of a submersible CT-sensor and a datalogger with battery package in a GRP enclosure. The CT-sensor contains a Pt-type temperature sensor and an inductive conductivity sensor. The data logger collects sensor readings at a programmable rate, calculates the averages and records the results, including a time stamp, for later retrieval.

Technical specifications:

Temperature
type: platinum
range: -5 to + 45°C
resolution: 0.1°
accuracy: 0.1°C

Conductivity
type: inductive
range: 0 to 100 mS/cm
resolution: 0.1 mS/cm
accuracy: 0.2 mS/cm (measurement of salinity level better than 0.1 ‰)

Datalogger
sampling interval: 1 s to 60 s
input accuracy: 0.1%

clock accuracy:	1 minute per month
storage capacity:	9000 records (C, T and time)
power supply:	10 to 16 VDC

3.2.5 Definition of salinity

The mass quantity of dissolved salts per unit of water mass or water volume is usually refered to as *salinity* (S). Seawater contains about 35 grams of salts per 1000 grams or liter of water; consequently the salinity S amounts to 35 parts per thousand (ppt, per mille, ‰, or g/l). Sometimes the quantity *cloridity* (Cl) is used; this measure represents the mass quantity of cloride ions per 1000 grams or liter of water. The relationship between these two quantities is:

$S = 0.03 + 1.905.Cl$ (valid for S and Cl > 1 ‰)

There is reasonable general agreement that the chloridity Cl of fresh water (suited for drinking water) should not exceed 200 – 250 mg/l (0.2 – 0.25 ppt). This fresh-water limit corresponds to a salinity value of 0.4 – 0.5 ppt.

In the present study we use the quantity *salinity* for the indication of the salt content of the water. When the salinity is determined with the help of measurement techniques based on conductivity, practical salinity units (psu) are applied. The scale of the practical salinity units is such selected that psu values are very close to ppt units of salinity. Therefore, we use ppt units of salinity in this report although the salinity values are measured in psu units.
The psu value of distilled water is chosen as zero. Fresh tap water with zero salinity has a very small psu value because of other dissolved, conductor elements. This zero-salinity psu value may differ for each individual instrument and has to be determined prior to execution of the measurements at the side. The measurements have to be corrected with this zero-salinity psu value.
The lower measurement limit of the CTD's amounts to about 0.1 ppt salinity; the measured values are not reliable below this limit value.

3.2.6 Execution of measurements

Zero-salinity measurements were carried out each day before the start of the actual measurements. To that purpose the CTD instrument was placed in fresh tap water and the psu value measured. Figures 3.5 and 3.6 present some of the measured psu values (wet season measurements) which correspond to zero salinity. These figures show that the zero-salinity psu values vary a little as a function of time. The zero-values are also different for the two used instruments (no. 718 and no. 726); the average zero-values are 0.172×10^{-3} and 0.065×10^{-3} respectively; the difference between the two instruments is approximately 0.1‰. In the dry season average zero-values appeared to be 0.15×10^{-3} and 0.04×10^{-3} (see Figures 3.7 and 3.8).
The psu values which were measured in the lakes and upper locks (wet season) have been corrected with the zero-values prior to presentation in figures in the separate Annex A.
Note: *The results of the dry-season measurements in lakes and upper locks are presented in the original form in figures in the separate Annex B.*

In the initial stage of the surveys the instruments were so programmed that salinity levels were measured at a vertical interval of 0.1 m. Later it was decided to change this approach and to carry out the measurements every 0.2 s with the direct reading option of the instruments. In this way the measurements could be followed on a laptop that was installed on the survey vessel. The laptops were provided with power from the batteries of the survey boats, which was converted into 220 Volt by a voltage converter.

In the case of vertical-salinity-profile measurements the CTD instrument was lowered with a constant speed until the bottom was reached. Subsequently the instrument was raised with a constant speed up to the water surface. The instrument was than taken out so that the survey boat could sail towards the next location. In case that the sensors were stained with some mud from the bed the instrument was cleaned with water. During short pauses between measurements the instrument was wrapped in wet towels.

In phases 1, 3 and 4 (see Section 3.2.2) vertical salinity profiles have been measured in longitudinal sections of the lock chambers. Initially, the two survey boats were measuring simultaneously in the same chamber. The two teams carried out measurements in long sections at a constant distance to the lock wall of approximately one third of the lock width. In most cases, if there was sufficient time in view of a smooth lock operation, vertical salinity profiles were measured at six locations in the longitudinal direction of the lock. No significant differences were found between measurement results of corresponding locations in the two long sections. Therefore it was decided to carry out measurements in a lock chamber with one survey boat only. Long sections were from that moment executed in the centre line of the lock chambers.

The centre wall and side walls of the lock chambers are provided with numbers, which indicate the distance in feet to the upstream and downstream gates. These numbers have been used to identify and characterise the locations where the measurements in the locks were carried out. In some of the locks these numbers were not visible from the survey boats. In that case one person on top of the centre wall indicated the location where the measurements had to be carried out.

Measurements outside the locks required a different approach for indication of the location of the measurements. In the forebays and tailbays of the locks positioning was done on the basis of visual observation of apparent marks on lock walls and wing walls. In the lakes and sea entrances the locations were noted from a global positioning system instrument, which indicated the location in UTM coordinates.

A number of measurements has been carried out near the water intakes and outlets of the locks. In those cases the survey boat was positioned beside the intake or outlet and the CTD instrument was kept at a stationary position in the flow.

In addition to the two CTD instruments a single CT instrument with logger was used to measure the salinity during a longer period of time at a number of fixed positions in tailbays and forebays, both at the Pacific and Atlantic side. The instrument was hanging free in the water and fixed to the centre wall or wing wall with the help of a cable. The instrument was at first positioned near to the bed and than lifted to a position near to (the low-tide) water surface. The CT instrument was programmed to do measurements every 10 minutes.

3.3 Visual observations during measurements

In this section we describe some of the visual observations during execution of the measurements.

Tailbay and forebay of Miraflores Locks

The approach wall / centre wall in the tailbay of Miraflores Locks is a solid wall (there are no connecting flow openings between east and west lane). Density currents occur in the tailbay when water is released from the lower lock chambers. It is known from experience (source: ACP) that the spilled water with lesser density may follow a path in the upper region of the water along the wing walls towards the banks of the entrance. Because of the local geometry the spill-water current in the east lane may reflect at the east bank and bends back towards the nose of the approach wall. It may thus cause undesired, transverse forces on a northbound vessel that is slowly approaching the wall.

After opening of the lock gates the salt water of the tailbay enters the lock chamber. This density current occurs in the lower region of the water; simultaneously a reverse, outgoing current occurs in the higher region. As a result again, density-flow forces may act on a vessel that is approaching.

To prevent these density-flow forces on approaching northbound vessels the water in the lower lock chambers of Miraflores Locks is levelled down immediately after a vessel has moved to the upper lock chamber; subsequently the downstream gates of the lower lock are opened to facilitate the outflow of water. This is the normal uplockage operation procedure. As a consequence, the water in the lower lock chamber is for the greater part replaced by the saltier water from the tailbay, when the next vessel enters.
Density currents are thus considerably weaker at the moment that the next vessel arrives. Yet, pilots of ships approaching in the west lane may still experience forces, which tend to push the bow of the ship towards the west wing / side wall (some accidents are reported).

In general, a next northbound vessel approaches when the spillage of lock water has already come to an end. In the case of busy traffic a ship may arrive shortly after the previous one. This ship is only allowed to proceed along the approach wall after spillage has stopped.

The procedure that is applied for uplocking ships is not required for downlocking ships. The downstream gates of the lower lock are opened immediately after spillage of the lock water and are closed as soon as the ship has left the lock. The vessel is untied from the locomotives and sails away at a relatively high speed along the approach wall. Hindrance of density currents is not reported. The culverts between the lower lock chamber and the tailbay are kept open at incoming tide so that the water level in the chamber can rise with the water level in the tailbay. This is required to prevent forces which may push open the lock gates.

The lower lock chamber is filled from and equalized with the water in the higher lock chamber at the moment that the next downlocking ship is in the upper lock chamber. Until that moment the water in the lower lock chamber is in open connection with the water in the tailbay, for the gates in the main culverts in side wall and centre wall are kept open. This operational measure is necessary to prevent the opening of the lock gates by the rising water

level in the tailbay at incoming tide. Some water from the tailbay may thus enter the lower lock chamber.

The water that is spilled from the lower lock chambers of Miraflores Locks emerges from the low-situated spill openings in side walls and centre wall as a highly turbulent jet (Photograph 11), spreads across the width of the channel between centre wall and side wall and proceeds in downstream direction. Visual observations indicate that the water spilled from the lower locks has a tendency to spread further in the wider parts of the tailbay and to move also towards the banks of the tailbay (Photograph 12).

The approach wall in the forebay of Miraflores Locks is a solid wall, similar as the approach wall in the tailbay. Southbound ships wait along the approach wall until the intake of water from the forebay has ended. The intake openings in side walls and centre wall are situated above the floor and are ample below the water surface. The flow towards the openings is smooth; large vortices were not observed at the water surface near the intakes.
When large water quantities are released from Miraflores Lake through the spillway beside Miraflores Locks (east side) approaching southbound ships may experience cross currents.

The gates of the upper locks of Miraflores Locks are closed as soon as a vesssel has left or entered a chamber. Nevertheless, gates may be open during a longer period of time when a number of smaller ships is approaching and entering a lock.

Tailbay and forebay of Pedro Miguel Locks

Approach walls in the tailbay and forebay of Pedro Miguel Locks are solid walls, similar as at Miraflores Locks. Gates of the locks are closed as soon as ships have entered or left a lock chamber. So-called hydraulic assist is given to southbound ships with large draught and beam when they exit the lock chamber (some additional water is supplied behind the ship to facilitate an easier sailing).

Tailbay and forebay of Gatun Locks

Approach walls in tailbay and forebay of Gatun Locks consist partly of solid walls and are partly composed of open arches (the portion from a line through the wing wall edges to the outer edge of the centre wall). The open arches are partly closed by steel panels to prevent spill currents to cross from one lane to the other.
As was observed, spill flows from the east lane tend to bend away and follow the east bank.

Locks

Normally, shipping in east and west lanes is in the same direction. Operation of the locks in both lanes is fully independent (Photograph 1). Cross filling of lock chambers is not applied, but sometimes, when a smooth operation requires so, some water may be discharged from one lock chamber to the neighbouring chamber in the other lane.

When a lock chamber is filled with water from the adjacent higher basin, filling jets coming up from the openings in the floor are visible at the water surface of the lock chamber (Photograph 9). In many cases the water in these jets has a different colour than the receiving water in the chamber. During measurements in Gatun Locks in the wet season

colour differences were very clear. The lake water was dark greenish, while the water in the tailbay was brownish. Ships were sailing northwards (downlockage). In the upper lock chamber the water had the same colour as the water in the lake; when the chamber was filled with water from the lake, the colour did not change. When the middle lock chamber was filled with water from the upper lock brownish jets were visible, which changed the colour of the water over the full surface. The same phenomenon occurred during filling of the lower lock with water from the middle lock, but the fill water was more brownish. When the lower lock was emptied the spill water formed a front (clearly visible at the water surface because of colour differences) that propagated in the tailbay. After opening of the miter gates of the lower lock a second front was formed that propagated after the first front. Opening of the miter gates generated local upwards flows about the edge of the gates and in the space between gates and recesses; the rising water in these flows was also brownish of colour.
Similar observations as described for downlockage were made in the lock chambers during uplockage of a ship in the wet season. After the ship had moved from the lower lock chamber (with high water level) to the middle lock chamber the brownish water in the lower lock chamber became more greenish. This phenomenon became even more apparent after the water in the lower lock chamber was levelled down to the tailbay level.

All these observations indicate that the density of the water increases going from higher lock to middle lock and lower lock. And also that the water that is drawn from a lock chamber to fill the adjacent lower chamber comes from the lower region in the higher chamber. Apparently, some layering occurs in certain phases of the lockage process. As was checked, the water temperature had almost a constant value of about 28° C throughout forebay, lock chambers and tailbay in the period of above observations, and was thus not of influence on density phenomena.

Other observations: When a lock chamber is filled, the upward filling jets arise initially near the upstream side of the chamber; than the number of jets extends in downstream direction. The greatest discharge comes at first from those fill openings which are farthest away from the main culvert in the lock wall. This can be concluded from the dimensions of the jets. Translatory waves which may indicate a strong unequal filling of the lock chamber, were not observed.
The filling jets cause turbulence in the water. The fill water spreads across the lock chamber area and the surface water becomes uniform of colour. After filling the water surface is still unquiet during some time: eddies are visible which die out slowly. When a ship is in the lock chamber during filling similar phenomena can be observed at the upstream and downstream sides of the ship. Filling times are approximately 10 minutes, depending also on single-culvert filling (filling from main culvert in side wall) or double-culvert filling (filling from main culvert in side wall and centre wall) and initial head.
The withdrawal of water from a lock chamber (through the openings in the floor) is a very quiet and smooth process. Neither important vortices near the water surface were observed nor translatory waves. The colour of the water in the lock chambers did not change during withdrawal of water, indicating that the water is mainly drawn from the lower water region of the lock chamber and that upwards flows do not occur during levelling down.
When water levels in adjacent basins have been equalized, density differences and / or a water level difference caused by over travel force the lock gates to open a little (a small gap becomes visible between the two miter gates). When the gap has formed the operator gets a signal from a 'proximity switch' and opens the gates.

Density differences between two adjacent basins cause density flows when the miter gates between these basins are opened. Photograph 8 shows the density current between the partly opened downstream gates of the lower lock at Miraflores. The existance of density flows was also experienced by the crew of the survey boats when they moved in for measurements.
The density flow towards the lower basin was in particular visible at the water surface in the lower locks of Miraflores Locks and Gatun Locks and in the tailbays (simultaneously a non-visible return current near the bottom entered the upper basin, see also Figure 3.10). At one occasion a propagation speed of about 0.7 m/s was observed for the front of the surface current in the lower chamber of Miraflores Locks (Photograph 10); at an other occasion a propagation speed of about 0.25 m/s was observed in the upper chamber of Miraflores Lock (both during uplockage of a small ship; ship in lower basin). This difference in propagation speed corresponds to a smaller density difference between forebay and upper chamber on the one hand and a greater density difference between upper chamber and lower chamber on the other hand. During downlockage of a ship a propagation speed of about 0.5 m/s was observed in the lower chamber of Miraflores Locks (ship in upper chamber), which is smaller than the speed of 0.7 m/s during uplockage. This indicates that density differences between upper and lower chamber of Miraflores Locks are smaller during downlockage than during uplockage, which may be the result of a different operation procedure (during uplockage, gates of the lower lock are kept open when possible).

When a big ship with large beam and draught enters a lock chamber, the piston effect of the ship at the entrance causes a translatory wave. As a result the water level near the closed gates may temporarily rise about 0.5 m or even more. When the water level is high in the chamber (downlockage) water may spill over the crest of the downstream gates, as was observed.
A ship that enters or exits a chamber usually uses it's own propellor or is pushed by a pushtow (Photograph 7). Clearly, the water behind the ship is locally mixed up, in particular at a low water level in the lock chamber (downlockage) and when the ship uses much power (big ships with large blockage ratio require more power than small ships). In the case of a high water level in the lock chamber (uplockage) the screw race of the ship may cause a spilling of water over the crest of the downstream gates, as was observed.
When a ship moves from one lock chamber to another lock chamber (or forebay / tailbay) eddies are visible at the bow of the ship. These eddies indicate that the return current along the ship draws the water from the region near to the ship's bow. Flow velocities in the return current may be high, causing a considerable local water surface draw down.

3.4 Wet-season data collection

3.4.1 Realised measurement programme

Annex A contains tables and figures with results of the measurements in the wet season. The first table – 'Outline of salinity measurements in wet season' – presents an overview of locations where salinity measurements have been carried out. An overview of measurements is given in a table for each location separately. These tables contain information on hydraulic conditions, vessel dimensions, position, date and time of measurements, and file

identification. The filename is composed of date, name of surveyor and time. The tables in Annex A are organized in the following groups:

- Outline of salinity measurements wet season
- Measurements Lock A (lower lock Miraflores Locks)
- Measurements Lock B (upper lock Miraflores Locks)
- Measurements Lock C (Pedro Miguel Locks)
- Measurements Lock D (lower lock Gatun Locks)
- Measurements Lock E (middle lock Gatun Locks)
- Measurements Lock F (upper lock Gatun Locks)
- Measurements in Pacific Entrance
- Measurements near Miraflores Locks
- Measurements in Miraflores Lake
- Measurements near Pedro Miguel Locks
- Measurements in Gaillard Cut
- Measurements in Gatun Lake
- Measurements near Gatun Locks
- Measurements in Atlantic Entrance

The position of measurement points outside the locks is indicated in m Easting and m Northing, according to the UTM projection system. These coordinates were determined with a global positioning system instrument (see also Section 3.2.6). Salinity measurements have been carried out in the entire reach of the Panama Canal from the Pacific Entrance, the Miraflores Lake, the Gaillard Cut, the Gatun Lake towards the Atlantic Entrance. Figure 3.9 presents a map with the positions of the measurement points in the Panama Canal area.

As discussed before, it was not possible to continuously measure the salinity levels and changes of salinity throughout the lock chambers during the full uplockage or downlockage process. Measurements in the lock chambers, therefore, were limited to next five phases (see also Figures 3.1 and 3.2):

Phase	*Uplockage*	*Downlockage*	*Measurements*
1	Low water level in lock, d/s gates are open.	High water level in lock, u/s gates are open.	Salinity profiles in long sections prior to entering of the ship.
2	Low water level in lock, d/s gates are open, vessel is sailing into lock.	High water level in lock, u/s gates are open, vessel is sailing into lock.	Salinity profiles at fixed position near closed gates ahead of the ship that moves in.
3	High water level in lock, u/s gates are open, vessel is sailing out of lock.	Low water level in lock, d/s gates are open, vessel is sailing out of lock.	Salinity profiles at fixed position near closed gates astern of the ship that moves out.
4	High water level in lock, gates are closed, lock is empty.	Low water level in lock, gates are closed, lock is empty.	Salinity profiles in long sections after the ship has left and the gates are closed.
5	Low water level in lock, gates are closed, lock is empty.	High water level in lock, gates are closed, lock is empty.	Salinity profiles in long sections after the water has levelled down (uplockage) or levelled up (downlockage) and prior to opening of the gates.

Table 3.1 Definition of uplockage and downlockage measurement phases in lock chambers

Results of the wet-season salinity measurements are presented in figures in Annex A. These figures are organized in the following groups:

- Lock A, Uplockage
- Lock A, Downlockage
- Lock B, Uplockage
- Lock B, Downlockage
- Lock C, Uplockage
- Lock C, Downlockage
- Lock D, Uplockage
- Lock D, Downlockage
- Lock E, Uplockage
- Lock E, Downlockage
- Lock F, Uplockage
- Lock F, Downlockage
- Pacific Entrance
- Miraflores Lake
- Gatun Lake
- Gatun Locks to Pedro Miguel Locks
- Measurements in outflow, inflow and filling jets
- Atlantic Entrance
- CT-logger at fixed position
- Measurements near Pedro Miguel Locks
- Measurements near Gatun Locks
- Measurements near Miraflores Locks

Most figures concern vertical salinity profiles. The salinity (in ppt) is plotted versus the depth (in m) below the water surface. Salinity profiles which were measured in the lock chambers, are shown for each measurement phase and each measurement position separately. Salinity profiles measured at one position (for example near the closed gates in phases 2 and 3) are combined in one figure. The position of the salinity profile and the time of measurement is indicated in the figures. Many salinity profiles were measured in the lakes and the sea entrances; only a representative part of these profiles was selected for presentation in Annex A. The continuous salinity measurements in forebays and tailbays, recorded with the CT-logger, are shown in figures as a function of time.

The water level in Gatun Lake was about PLD +87.3 ft (PLD +26.6 m), in Miraflores Lake PLD +54.5 ft (PLD +16.6 m).

3.4.2 Discussion of measurement results

The results of the measurements are discussed briefly in this section. It should be noted that the salinity measurements in lock chambers represent momentarily values at different moments of time and for different ships; they do not represent the actual salinity changes during a full up- or downlockage process of a single ship.

Water temperatures were simultaneously measured with conductivities and depth. In the wet season temperatures appeared to be almost constant throughout the entire canal system

(Pacific tailbay, Miraflores Locks, Miraflores Lake, Pedro Miguel Locks, Gaillard Cut. Gatun Lake, Gatun Locks, Atlantic tailbay). Temperatures were between 27.5 and 28.5 °C, and because of the constant value, temperature was not a relevant influencing factor for density currents.

Miraflores Locks (Locks A and B) and Pedro Miguel Locks (Lock C)

Lock A, uplockage.
Results of measurements in Lock A are presented in Figures A1 – A13.

phase 1, downstream gates are open, low water level in lock chamber, ship is in tailbay
phase 2, downstream gates are open, low water level in lock chamber, ship is entering

- prior to entry of ship: density differences cause an exchange of water; the salt water tongue enters lock A, reflects against the closed upstream end of the lock chamber and returns to the open end (see Figure 3.10 for explanation of process, and Figure A6 for measured process); as a result a layered water system develops; the propagation velocity of the front of the density current depends on density difference and water depth and can be estimated as between 0.5 and 1.0 m/s
- the salinity of the lower layer is high and equal to the salinity of the water in the tailbay (about 28 ppt); an upper layer is present where the salinity is much smaller and decreases towards the water surface
- the longer the downstream gates are open, the more the exchange process proceeds and the more the upper layer with lesser salinity reduces; however, a full replacement with salt water from the tailbay is not reached, a top layer with lesser salinity remains; it may take about 0.5 hour to arrive at this situation
- significant gradients of salinity do not occur in transverse direction of the lock chamber
- no data are available on effects during entry of ship

phase 3, upstream gates are open, high water level in lock chamber, ship is exiting
phase 4, upstream gates are closed, high water level in empty lock chamber

- filling of the lock chamber with water from the higher Lock B reduces the salinity; because of the intensive mixing process, a rather uniform salinity in the vertical direction results (see Figure A11, measurements without a vessel)
- in the case of high tide less fill water is required than in the case of low tide and consequently the salinity in the lower Lock A reduces less than at low tide
- when the ship exits the lower Lock A and moves to Lock B, water with lower density and lower salinity enters from Lock B; as a result the salinity in Lock A reduces further but the ship-induced supply of water causes density currents and layering

phase 5, gates are closed, low water level in empty lock chamber, water levelled down

- emptying of the lock chamber does not strongly influence the salinity distribution in the remaining water in vertical direction: the water is mainly drawn from the lower water region (with highest salinity) while the salinity gradient in the upper water region is hardly effected
- after levelling down there is a varying salinity gradient in vertical direction rather than distinct layers with different salinity

Lock B, uplockage.
Results of measurements in Lock B are presented in Figures A14 – A19.

phase 1, downstream gates are open, low water level in lock chamber, ship is in lock A

phase 2, downstream gates are open, low water level in lock chamber, ship is entering

- prior to entry of ship: similar as between tailbay and lower lock, density differences cause an exchange of water between lower and upper lock; the water in the lower lock has earlier been mixed up during the filling process; the exchange flow occurs in the upper water region of the lower lock above the level of the upward step in the floor, leaving at rest the water in the lower region; when no vessel enters in the upper lock (Figure A14) the salt water tongue in the upper lock may fully develop; in that case salinities near the floor of the upper lock may go up to 20 ppt
- when the ship enters the upper lock a counter acting effect occurs: the return current along the ship hull obstructs a further intrusion of water with higher density and higher salinity and may even force the intruded saltier water to flow back (Figure A15)

phase 3, upstream gates are open, high water level in lock chamber, ship is exiting

phase 4, upstream gates are closed, high water level in empty lock chamber

- filling the lock chamber with water from the forebay reduces the salinity
- no data are available on effects during exit of the ship
- after exit of the ship and closure of the gates still internal density waves are present (Figures A16 and A17); layering occurs

phase 5, gates are closed, low water level in empty lock chamber, water levelled down

- similar as in the lower lock, the salinity distribution in the remaining water in vertical direction is not strongly effected by the emptying process: the water is mainly drawn from the lower water region (with highest salinity)
- similar as in the lower lock, after levelling down there is a varying salinity gradient in vertical direction rather than distinct layers with different salinity

Lock C, uplockage.

Results of measurements in Lock C are presented in Figures A20 – A23.

phase 1, downstream gates are open, low water level in lock chamber, ship is in tailbay

phase 2, downstream gates are open, low water level in lock chamber, ship is entering

- the salinity is nil or almost nil throughout the entire lock chamber prior to entry of ship (a number of other ships has already preceded this ship)

phase 3, upstream gates are open, high water level in lock chamber, ship is exiting

phase 4, upstream gates are closed, high water level in empty lock chamber

- after filling with water from Gaillard Cut salinity levels are unchanged
- during and after exit of vessel no density currents are noticeable

phase 5, gates are closed, low water level in empty lock chamber, levelled down

- emptying of the lock chamber does not effect the salinity levels: salinity is nil or almost nil throughout the lock chamber

Lock C, downlockage.

Results of measurements in Lock C are presented in Figures A24 – A27.

phase 1, upstream gates are open, high water level in lock chamber, ship is in forebay

phase 2, upstream gates are open, high water level in lock chamber, ship is entering

- prior to entry of ship (first downlocking ship after turn around) salinity levels are nil in entire lock chamber
- a low salinity level of 0.1 ppt is present near the downstream gates during entering of the ship (after a series of other ships have locked down); apparent gradients in the vertical direction do not occur

phase 3, downstream gates are open, low water level in lock chamber, ship is exiting
phase 4, downstream gates are closed, low water level in empty lock chamber

- after the water has levelled down and the ship has left the lock chamber higher salinity values up to 0.3 ppt are found near the downstream gates; apparent gradients in vertical direction do not occur, but towards upstream gates salinity values decrease to 0.05 ppt (note: with small density differences propagation velocities of density currents are small, up to about 0.2 m/s); apparently the ship-induced supply of water from Miraflores Lake into the lock chamber has caused higher salinity values
- no data are available on effects during exit of ship

phase 5, gates are closed, high water level in empty lock chamber, water levelled up

- after filling with water from the forebay in Gaillard Cut salinity values are lower; gradients do not occur in vertical direction but salinity values decrease towards upstream gates

Lock B, downlockage.
Results of measurements in Lock B are presented in Figures A28 – A36.

phase 1, upstream gates are open, high water level in lock chamber, ship is in forebay
phase 2, upstream gates are open, high water level in lock chamber, ship is entering

- prior to entry of ship: density differences cause an exchange of water between forebay and upper lock chamber of Miraflores Locks; the water in the lock chamber has earlier been mixed up during the filling process (resulting in a rather uniform salinity throughout the empty lock chamber of 2 – 4 ppt), and the exchange flow occurs mainly in the upper water region of the lock above the level of the downward step in the floor (Figure A28, no vessel, layering effects)
- when the ship enters the upper lock chamber the return current along the ship hull causes the outflow of more saline water from the lock chamber to the forebay
- significant differences in transverse direction of the lock chamber do not occur

phase 3, downstream gates are open, low water level in lock chamber, ship is exiting
phase 4, downstream gates are closed, low water level in empty lock chamber

- after the water has levelled down the exit of the ship causes an inflow of water from the lower lock; salinity gradients are present in vertical direction and internal density waves occur in the closed lock chamber after the ship has left
- significant differences in transverse direction of the lock chamber do not occur

phase 5, gates are closed, high water level in empty lock chamber, water levelled up

- after filling with water from the forebay in Miraflores Lake salinity values are more or less uniform in vertical direction as a result of mixing

Lock A, downlockage.
Results of measurements in Lock A are presented in Figures A37 – A44.

phase 1, upstream gates are open, high water level in lock chamber, ship is in upper lock
phase 2, upstream gates are open, high water level in lock chamber, ship is entering

- prior to opening of the gates between upper and lower lock, the lower lock (without ship) is filled with water with lesser salinity from the upper lock; because of mixing salinity in the lower lock becomes rather uniform (the salinity may have a value between 10 and 15 ppt, depending also on low tide and high tide; in the latter case lesser water is required to level up and consequently salinity in the lower lock will less reduce)

- when the gates are opened density differences cause density flows between upper lock and lower lock; which may fully develop when no ship is present (Figures A37 and A40), layering occurs
- during entering of the ship water is forced to flow from lower lock into the upper lock; after the ship has entered still strong gradients in vertical direction are present

phase 3, downstream gates are open, low water level in lock chamber, ship is exiting
phase 4, downstream gates are closed, low water level in empty lock chamber

- after the ship has exited salt water from the tailbay has entered the lock chamber; layering occurs; strong salinity gradients exist at the transition of lower layer to upper layer; internal density waves are present in the closed lock chamber
- significant differences in transverse direction of the lock chamber do not occur

phase 5, gates are closed, high water level in empty lock chamber, water levelled up

- no data on this phase available

Gatun Locks (Locks D, E and F)

Salinity measurements in Gatun Locks are more complete and more systematic than in Miraflores Locks and Pedro Miguel Locks. In general, hydraulic phenomena in Gatun Locks appear to be similar as in the locks at the Pacific side.

Lock D, uplockage.
Results of measurements in Lock D are presented in Figures A45 – A49.

phase 1, downstream gates are open, low water level in lock chamber, ship is in tailbay
phase 2, downstream gates are open, low water level in lock chamber, ship is entering

- after opening of gates: density differences between tailbay and lower lock chamber cause density currents; layering; salinity in lower layer up to 30 ppt; upper layer minimizes after gates are open during a longer period of time (Figure A45); strong gradient in salinity at transition from lower layer to upper layer
- entry of ship after the gates have been open during a longer period of time does not cause important changes in salinity levels; however, when the ship enters immediately after opening of the gates, the ship-induced return current may have a reducing effect on salt water intrusion, depending also on ship dimensions

phase 3, upstream gates are open, high water level in lock chamber, ship is exiting
phase 4, upstream gates are closed, high water level in empty lock chamber
phase 5, gates are closed, low water level in empty lock chamber, water levelled down

- after filling with water from the middle lock, the water is mixed up and the salinity (considerably smaller than before filling) is more or less uniform in vertical direction
- when the ship has moved from lower lock to middle lock, water with lesser salinity has entered the lower lock; some layering occurs; internal density waves in closed lock
- levelling down the water in the closed lock chamber does not strongly effect the salinity gradient in the remaining water: water is withdrawn from the lower region with highest salinity

Lock E, uplockage.
Results of measurements in Lock E are presented in Figures A50 – A54.

phase 1, downstream gates are open, low water level in lock chamber, ship is in lower lock
phase 2, downstream gates are open, low water level in lock chamber, ship is entering

- density currents develop between lower and middle lock after opening of the gates and prior to entry of ship; salt tongue (salinity about 10 ppt) proceeds along the floor of the middle lock
- because of the return current the entry of the ship may partly prevent the intrusion of water with higher salinity

phase 3, upstream gates are open, high water level in lock chamber, ship is exiting
phase 4, upstream gates are closed, high water level in empty lock chamber
phase 5, gates are closed, low water level in empty lock chamber, water levelled down

- after filling with water from the upper lock salinity gradients in the vertical direction are relatively small (the salinity may have a value between about 3 and 5 ppt)
- when the ship has moved from middle lock to upper lock, water with lower salinity has entered; after the gates have been closed some layering occurs and internal density waves are noticeable
- levelling down the water does not strongly effect the salinity gradient in the remaining water; water is drawn from the lower water region with highest salinity and spilled in the lower lock D

Lock F, uplockage.
Results of measurements in Lock F are presented in Figures A55 – A59.

phase 1, downstream gates are open, low water level in lock chamber, ship is in middle lock
phase 2, downstream gates are open, low water level in lock chamber, ship is entering

- salinity levels in upper lock are low (below 0.5 ppt)
- some density currents may occur after opening of the gates between middle and upper lock

phase 3, upstream gates are open, high water level in lock chamber, ship is exiting
phase 4, upstream gates are closed, high water level in empty lock chamber
phase 5, gates are closed, low water level in empty lock chamber, water levelled down

- ship that is exiting uses it's propellor and causes mixing behind the ship
- after the ship has left and the gates have been closed salinity gradients in vertical direction are small; salinity levels are below 0.3 ppt and decrease towards the upstream side of the lock chamber
- after levelling down, the salinity levels and gradients in the remaining water have not much changed

Lock F, downlockage.
Results of measurements in Lock F are presented in Figures A60 – A64.

phase 1, upstream gates are open, high water level in lock chamber, ship is in forebay
phase 2, upstream gates are open, high water level in lock chamber, ship is entering

- after levelling up and prior to entry of ship: salinity levels are low, below 0.3 ppt, no strong gradients in vertical direction, salinity is highest near downstream side of lock chamber; density currents not noticeable
- entry of ship causes no noticeable density current effects

phase 3, downstream gates are open, low water level in lock chamber, ship is exiting
phase 4, downstream gates are closed, low water level in empty lock chamber
phase 5, gates are closed, high water level in empty lock chamber, water levelled up

- after the water has levelled down gates are opened and the ship moves from upper lock to middle lock; the return flow brings water with higher density and higher salinity into the upper lock; internal density waves occur in the closed empty upper lock
- after filling with water from the forebay and mixing up the salinity is more or less uniform in the upper chamber; salinity values are below 2 ppt, and remarkably higher than 0.3 ppt in phase 1 (but these values were measured one day before the measurements in phase 5)

Lock E, downlockage.
Results of measurements in Lock E are presented in Figures A65 – A70.

phase 1, upstream gates are open, high water level in lock chamber, ship is in upper lock
phase 2, upstream gates are open, high water level in lock chamber, ship is entering
- after levelling up and prior to entry of ship: the salinity level is low (about 1 ppt) and almost uniform in lock chamber; density currents not measured
- entry of ship causes no noticeable density current effects in the middle lock

phase 3, downstream gates are open, low water level in lock chamber, ship is exiting
phase 4, downstream gates are closed, low water level in empty lock chamber
phase 5, gates are closed, high water level in empty lock chamber, water levelled up
- after the water has levelled down gates are opened and the ship moves from middle lock to lower lock; the return flow brings water with higher density and higher salinity into the middle lock; internal density waves occur in the closed empty middle lock, which are clearly shown in Figure A68 and Figure A69 (measurement at fixed position at different moments in time); these internal waves die out only very slowly
- after filling with water from the upper lock and mixing up the salinity is more or less uniform in the upper chamber; salinity values are about 1 ppt

Lock D, downlockage.
Results of measurements in Lock D are presented in Figures A71 – A76.

phase 1, upstream gates are open, high water level in lock chamber, ship is in middle lock
phase 2, upstream gates are open, high water level in lock chamber, ship is entering
- after levelling up and prior to entry of ship: density currents occur between middle and lower lock: a layer with lesser salinity propagates on top of the water in the lower lock; the salinity of the lower layer is between 5 and 7 ppt, but higher salinity values are present near to the floor
- entry of the ship causes a return flow to the middle lock

phase 3, downstream gates are open, low water level in lock chamber, ship is exiting
phase 4, downstream gates are closed, low water level in empty lock chamber
phase 5, gates are closed, high water level in empty lock chamber, water levelled up
- after the water has levelled down gates are opened and the ship moves from lower lock to tailbay; the return flow brings water with higher density and higher salinity into the lower lock; internal density waves occur in the closed empty lower lock, which are clearly shown in Figure A75 and Figure A74 (measurement at fixed position at different moments in time)
- after filling with water from the middle lock and mixing up the salinity is more or less uniform in the middle chamber; salinity values are about 12 ppt, which are much higher than initial values in phase 1 (but those values were measured at an other day)

Measurements near Miraflores Locks (Locks A and B), Pedro Miguel Locks (Lock C) and Gatun Locks (Locks D, E and F)

Salinity measurements have been executed in forebays and tailbays of Miraflores Locks (with emphasis on the tailbay), Pedro Miguel Locks and Gatun Locks. Salinity profiles were also taken in the approach channels in the sea entrances. These measurements were aimed to get insight in the effects of tidal movements, lock operations and shipping on salinity levels. Most of the salinity measurements concern vertical salinity profiles (which were taken from the water surface to the bed and back). Measurements in forebays and tailbays were programmed and executed independently of measurements in the locks; in the dry season measurements in locks and tailbays / forebays were simultaneously executed to get a better insight in the exchange processes between lock chambers and adjacent forebay / tailbay. Measurements at the nose of the approach wall in forebay and tailbay (fixed position) were executed with the CT-logger.

Miraflores Locks

Results of salinity measurements near Miraflores Locks are presented in Figures A96 – A115 (tailbay, along centre wall / approach wall and side walls), A124 (near outlet), A125 (near intake), A127 (CT-logger, tailbay, nose approach wall), A128 (CT-logger, forebay, nose approach wall), and A77-A78a/b (approach channel Pacific Entrance).

Measurements in the tailbay have been undertaken at different moments in time, both during incoming tide, falling tide and a period around low tide. The positions where the salinity profiles were measured are indicated in the figures.
The figures show that the salinity in the region near the bed is about 28 ppt. In the region near the water surface the salinity may go back to a value of about 20 ppt. The thickness of the upper layer where the salinity reduces depends mainly on the number of lockages (quantity of spilled water) and on pauses between lockage periods (the intermittent spill flow may be stopped during several hours). Very close to the gates of the locks this layered system is also apparent. Measurements near the outlet in the side wall (during spillage of water from the lower lock in the west lane, Figure A124) show that the local salinity near the surface may go back to about 10 ppt or less.
The tidal variation (incoming tide or falling tide) seems not to be very important for the salinity levels near the bed and near the surface in the area near to the locks. It is true that the tidal movement causes an inflow and outflow of water in the sea entrance, but horizontal tidal flow velocities near the locks are small and do not cause an important mixing up. As a result, only the thickness of the lower layer, where the salinity has a more or less constant value of about 28 ppt, varies with the tidal movement.

The continous measurements during four consecutive days with the CT-logger fixed on the nose of the approach wall in the tailbay (Figure A127) show a variation of the salinity with the tide. The CT-sensor was first positioned about 2 m below the low-tide water surface (near the local bed) and then lifted to a position about 1 m higher. The underwater structure of the wall did not allow a deeper positioning. Because of the relatively high position, the sensor measured salinity variations corresponding to the tidal-driven thickness variation of the underlayer (salinity of underlayer about 28 ppt). In the dry season similar measurements were excuted at the east wing wall at a position deeper below the water surface. In that case

an almost constant salinity of about 34 ppt was measured in the underlayer (see Figure B137), showing no influence of the tidal variation on the salinity in the underlayer.

The measurements do not show that the spill flows with lower salinity propagate as more or less concentrated density flows along west or east bank of the tailbay. On the contrary, it appears that the water with lower salinity spreads in the tailbay, as can be concluded from the measurements in the centre line of the approach wall, where a similar reduction of salinity in the upper water region is found as near to the banks.

Salinity measurements have been executed at a fixed position near the first green buoy in the shipping channel of the Pacific Entrance, west side, a few hundreds of meters south of the nose of the approach wall. The first series of salinity profiles was taken in a period with falling tide, low tide and incoming tide, covering also a window in time without shipping (Figure A78a). The second series was recorded in the morning hours at incoming tide (Figure A78b). The results show that the salinity of the underlayer has a constant value of about 28 ppt; near the water surface the salinity may go down to a value of about 18 – 22 ppt. Again, the tide seems not to mix up the water in the area near the locks: the thickness of the underlayer with salinity of about 28 ppt may vary but the toplayer with lesser salinity remains.
Figure A77 presents some selected salinity profiles, which were measured in two parallel longitudinal sections in the shipping channel in the Pacific Entrance, starting near the locks and ending at the Bridge of the America's. Measurements started at incoming tide, 2 hours before high tide, and continued till 1.5 hours after high tide. The salinity profiles show that the toplayer with lesser salinity is present in the entire channel.

In the forebay of Miraflores Locks salinity levels were measured during two consecutive days at the nose of the approach wall (Figure A128). It appears that salinity values roughly vary between 0.2 ppt and 1.0 ppt. Highest values are found near the bed. Variations are caused by ship passages, but possibly also by the flow towards Miraflores Spillway.

Pedro Miguel Locks

Results of salinity measurements near Pedro Miguel Locks are presented in Figures A92 and A93.

Measurements have been carried out in the forebay of Pedro Miguel Locks. Locations where salinity profiles have been taken are shown in the figures in Annex A. These locations are along wing walls and approach wall. Measurements were executed in the pause between morning-northbound vessels and afternoun-southbound vessels. As can be seen, salinity levels are zero or almost zero at the upstream side of of Pedro Miguel Locks.

Gatun Locks

Results of salinity measurements near Gatun Locks are presented in Figures A94 – A95 (forebay, along centre wall / approach wall), A130 (CT-logger, tailbay, nose approach wall), A129 (CT-logger, forebay, nose approach wall), and A120 – A123 (Atlantic Entrance.

Measurements along the approach wall in the forebay show that in the area near to the locks (up to about 500 ft away from the lock gates, between centre wall and side walls) small

quantities of salt are present. Salinity values are in the range up to about 0.2 ppt in the lower water region near the bed and may vary in dependence of lock operation and passing ships. The CT-sensor which was mounted on the nose of the approach wall in the forebay shows very low psu values of about 0.015 (Figure A129). The measurements with the CT-sensor were executed during two consecutive days; the first position was near to the local bed (which was however, not deep under the water surface) and the second position was near to the water surface. A psu value of 0.015 of the CT-sensor corresponds to a zero-salinity value. The salinity level at the upstream side of Gatun Locks was thus very low or zero during the measurements in the wet season.

The CT-sensor was earlier mounted to the nose of the north approach wall in the tailbay. Measurements were executed during four consecutive days. Similar as in the forebay the sensor was firstly positioned near to the local bed and than lifted to a position 1 m below the low-tide water surface (Figure A130). The tidal variation is small in the Atlantic entrance, only a few decimeters. The measurements show that the salinity in the lower water region is almost constant, about 31 ppt. Near to the water surface the salinity varies about a value of 25 ppt. The variations are solely caused by lock operation and ship passages; the tidal movement seems not to have a significant influence.

Vertical salinity profiles which were measured at different moments in time at a fixed position near the first green buoy in the shipping channel of the Atlantic Entrance, east side, are shown in Figures A120 (morning, falling tide) and A121 (afternoon, about low tide). The first green buoy is located a few hundreds of meters north of the approach wall. Again, salinity values are up to about 31 ppt in the region near to the bed and may go back to a value of about 15 ppt near the surface. The latter value is smaller than the value of 25 ppt near the water surface at the nose of the approach wall; it may indicate that spill flows in the east lane bend away to the east bank before they pass the outer end of the approach wall. This is conform the visual observations during the measurements. The passage of a big ship causes a local mixing up, resulting in a temporarily uniform salinity in the vertical direction (Figure A120).
Figures A122 and A123 present selected results of salinity profilings in two longitudinal sections in the shipping channel of the Atlantic Entrance. Measurements started near the locks and continued up to about 6.5 km away from the locks. The results show that salinity values in the region near the water surface may go down to about 2.5 ppt near the locks; at a greater distance to the locks salinity values near the water surface go up to about 25 ppt, but they remain smaller than the salinity values of about 31 ppt in the lower region near the bed. Clearly the continuous lockage operations produce a fresh water outflow, which causes a considerable reduction of the salinity in the upper water layer of the Atlantic Entrance.

Miraflores Lake

Selected results of salinity measurements in Miraflores Lake are presented in Figures A79 – A86.

Salinity profiles have been measured in two parallel, longitudinal sections in the shipping channel from Miraflores Locks to Pedro Miguel Locks (Figures A79, A80), in a long section along west and east bank of Miraflores Lake (Figures A81, A82), and in sections parallel and perpendicular to Miraflores Spillway.

Measurements in the shipping lane show that the salinity is about 0.5 ppt in the entire channel between Miraflores Locks and Pedro Miguel Locks, but near the bed salinity values are up to about 1.5 ppt (near to Pedro Miguel Locks smaller values up to about 1.0 ppt are found near the bed, while salinity values near the water surface may be smaller than 0.5 ppt). Salinity values near east and west bank of Miraflores Lake are about 0.5 ppt near the water surface and somewhat higher near the bed. Salinity values up to about 4 ppt are found near the bed in the forebay of Miraflores Locks.

Detailed measurements in sections near Miraflores Spillway show salinity values between about 0.3 ppt near the water surface and 0.8 ppt near the bed. The latter values are somewhat smaller than the values found near the bed in the shipping channel.

Gaillard Cut and Gatun Lake

Selected results of salinity measurements in Gaillard Cut and Gatun Lake are presented in Figures A87 – A91, and Figures A116 – A119.

Salinity measurements have been executed in a longitudinal section in the shipping channel from Gatun Locks to Pedro Miguel Locks (Figures A87 – A91). Vertical salinity profiles were taken at regular mutual distances, over the full length of the shipping channel. As can be seen in the figures, salinity values were zero in the entire channel.
Vertical salinity profiles were also taken in the deep berthing area of Gatun Lake, east of Gatun Locks. In this area profilings were done in longitudinal sections perpedicular to the bank of the lake (Figures A117 – A119). Salinity values appeared to be zero or almost zero.
The third area where salinity profiles were measured was the deep area near Gatun Spillway. Profiling was done in a longitudinal section from Gatun Locks along the west bank to the area near the spillway (Figure A116, deepest points about 35 m). Again, salinity values appeared to be zero or almost zero. The applied CTD's have a lower measurement limit of 0.1 ‰ salinity; this makes salinity measurements below a value of 0.1 ppt unreliable. A safe conclusion is therefore that the salt concentration of Gatun Lake and Gaillard Cut was smaller than 0.1 ppt during the measurements in the wet season.

3.5 Dry-season data collection

3.5.1 Realised measurement programme

Annex B contains tables and figures with results of the measurements in the dry season. The first table – 'Outline of salinity measurements in dry season' – presents an overview of locations where salinity measurements have been carried out together with relevant conditions. An overview of measurements is given in tables for each lock complex, for Miraflores Lake, Gaillard Cut and Gatun Lake separately. These tables contain information on hydraulic conditions, vessel dimensions, position, date and time of measurements, and file identification. The file name is composed of date, name of surveyor and time. The tables in Annex B are organized in the following groups:

- Outline of salinity measurements dry season
- Measurements Miraflores Locks (Lock A and Lock B)

- Measurements Pedro Miguel Locks (Lock C)
- Measurements Gatun Locks (Lock D, Lock E and Lock F)
- Measurements Miraflores Lake
- Measurements Gaillard Cut
- Measurements Gatun Lake

In addition to measurements in the lock chambers (for measurement phases see Table 3.1) simultaneous measurements in adjacent forebays or tailbays have been carried out in three phases of the lockage process (see also Figures 3.3 and 3.4):

Phase	*Uplockage*	*Downlockage*	*Measurements*
a	Water level in adjacent lock is levelled down, lock is empty.	Water level in adjacent lock is levelled down, vessel is in lock.	Salinity level of water that is spilled from adjacent lock into tailbay
b	Low water level in adjacent lock, d/s gates are closed, vessel is waiting in tailbay.	Low water level in adjacent lock, d/s gates are closed, vessel is waiting in lock.	Salinity profiles in long section in tailbay after spillage of lock water and prior to passage of vessel.
c	Vessel has passed tailbay, d/s gates of adjacent lock are closed, vessel is in lock.	Adjacent lock is empty, d/s gates are closed, vessel has passed tailbay.	Salinity profiles in long section in tailbay after passage of vessel and prior to next spillage of lock water.

Table 3.2 Definition of uplockage and downlockage measurement phases in tailbays

Phase	*Uplockage*	*Downlockage*	*Measurements*
a	Water level in adjacent lock is levelled up, vessel is in lock.	Water level in adjacent lock is levelled up, lock is empty.	Salinity level of water that is taken in from forebay into adjacent lock.
b	High water level in adjacent lock, u/s gates are closed, vessel is waiting in lock.	High water level in adjacent lock, u/s gates are closed, vessel is waiting in forebay.	Salinity profiles in long section in forebay after withdrawal of water and prior to passage of vessel.
c	Adjacent lock is empty, u/s gates are closed, vessel has passed forebay.	Vessel has passed forebay, u/s gates of adjacent lock are closed, vessel is in lock.	Salinity profiles in long section in forebay after passage of vessel and prior to next withdrawal of water.

Table 3.3 Definition of uplockage and downlockage measurement phases in forebays

Measurement phases in locks are indicated with numbers 1 – 5 and in forebays / tailbays with letters a – c; in some cases an exclamation mark is placed behind number or letter in the tables in Annex, for example 2!. This mark indicates that conditions during measurements were divergent from the 'usual' conditions. The meaning of the marks is as follows:

2! salinity profiles are taken in the lock chamber at a fixed position astern of the ship (after the gates are closed, but prior to filling or emptying) instead of ahead of the ship
3! salinity profiles are taken in the lock chamber at a fixed position ahead of the ship (before the gates are opened) instead of astern the ship
4! salinity profiles are taken in the empty lock chamber in a long section after the water has levelled up (down) and levelled down (up) again, without ship

b! salinity profiles are taken in a long section in tailbay / forebay, but no ship waiting for passage

c! salinity profiles are taken in a long section in tailbay / forebay, but no passage of ship

Results of the dry-season salinity measurements are presented in figures in Annex B. These figures are organized in the following groups:

- Miraflores Locks (Locks A and B), Uplockage
- Miraflores Locks (Locks A and B), Uplockage high tide
- Miraflores Locks (Locks A and B), Uplockage low tide
- Pedro Miguel Locls (Locks C), Uplockage
- Pedro Miguel Locls (Locks C), Downlockage
- Miraflores Locks (Locks A and B), Downlockage
- Miraflores Locks (Locks A and B), Downlockage high tide
- Miraflores Locks (Locks A and B), Downlockage low tide
- Gatun Locks (Locks D, E and F), Uplockage
- Gatun Locks (Locks D, E and F), Downlockage
- Miraflores Lake
- Gaillard Cut
- Gatun Lake
- CT-logger at fixed position

Similar as with the presentation of wet-season results in Annex A most figures in Annex B concern vertical salinity profiles. The salinity (in ppt) is plotted versus the depth (in m) below the water surface. Salinity profiles which were measured in the lock chambers, tailbays and forebays are shown for each measurement phase and each measurement position separately. Salinities measured at one position (for example: phase a, measurements near the outlet or intake of locks) are combined in one figure. The position of the salinity profile and the time of measurement is indicated in the figures. A representative part of the salinity profiles which were measured in the lakes, was selected for presentation in Annex B. The continuous salinity measurements in tailbays, recorded with the CT-logger, are shown in figures as a function of time.

The water level in Gatun Lake was about PLD +85.5 ft (PLD +26.1 m), only 0.5 m lower than in the wet season; the water level in Miraflores Lake was PLD +54.5 ft (PLD +16.6 m), similar as in the wet season.

3.5.2 Discussion of measurement results

The results of the salinity measurements are briefly discussed in this section. The emphasis is on the hydraulic processes in forebays and tailbays in coherence with the processes in adjacent lock chambers. Salinity levels in the lakes are compared with salinity levels which were measured in the wet season.

The temperature of the water was simultaneously measured with conductivity and depth. The water temperature in the Pacific Entrance near the locks appeared to be much lower than in the wet season: about 21 °C (versus 28 °C in the wet season), while the temperature in the Atlantic Entrance was still the same (about 28 °C). Consequently there were also lower temperatures in Miraflores Locks going up from 22 °C in the lower lock A to about 28

°C in the forebay in Miraflores Lake. The temperature in Miraflores Lake, Pedro Miguel Locks, Gaillard Cut, Gatun Lake and Gatun Locks appeared to have a more or less constant value of about 28 °C. Both a higher salinity and a lower temperature cause a higher density; the lower temperature in the Pacific tailbay may thus have caused stronger density currents between tailbay and lower Lock A, between lock A and Lock B and between Lock B and the forebay in Miraflores Lake.

Miraflores Locks (Locks A and B) and Pedro Miguel Locks (Lock C)

Tailbay Miraflores Locks (Pacific side)

Continuous salinity measurements during about 5 consecutive days were done in the tailbay with the CT-logger. The sensor was fixed at the outer edge of the wing wall in the eastern tailbay. The sensor was first positioned near the local bed and was than lifted to a position near the low-tide water surface. Results of these measurements are shown in Figure B137.

It appears that the temperature near the bed is a little below 21 °C and near the water surface above 21 °C; in the latter case the temperature fluctuates with the tide. The salinity is more or less constant at the position near the bed and fluctuates in the higher position with the tide, similar as the temperature. As was earlier explained in Section 4.2.3 the tide causes an inflow and outflow of saline water, but horizontal flow velocities are small near the locks. As a result, the thickness of the underlayer (which has a more or less constant salinity and temperature) varies. The upper layer with lesser salinity, which is caused by the spillages from the locks, is moving up and down with the thickness variation of the underlayer, but is not mixing up with the underlayer.

Remarkably, the salinity of the underlayer is much higher in the dry season than in the wet season (34 ppt versus 28 ppt) and the temperature lower (20.5 °C versus 27.5 °C). Possibly, these differences are caused by seasonal variations in the flows towards the Pacific coast.

Miraflores Locks, uplockage

Measurements have been executed in Lock B and forebay. Results of measurements are presented in Figures B1 – B15.

Lock B

phases 2!, 3!, 3, 4, 5, 4!

- after the ship has moved from Lock A to Lock B and gates are closed a thin water layer with high salinity (up to about 20 ppt) is present near the floor at the downstream side of the lock chamber (Figure B1)
- after filling with water from the forebay the salinity level at the downstream side of the lock chamber is rather uniform in vertical direction, about 6 – 7 ppt (Figures B2 and B3); the fill water has a salinity of about 2.0 ppt (Figure B9)
- when the ship moves out to the forebay, water with lesser salinity enters the lock and forms a layer at the surface; after the upstream gates have been closed a thin layer with higher salinity is also noticeable near the floor (Figure B4); the water system is not at rest; internal waves occur
- levelling down: water is withdrawn from the lower water region with highest salinity;. this causes a reduction of the average salinity; after levelling down strong vertical salinity gradients are still there; gradients vary in longitudinal direction (Figure B5)
- when the lock chamber is filled again (Figure B6), but without a next ship, the vertical salinity distribution becomes more or less uniform, about 3.5 – 4 ppt (fill water has a salinity of about 2 – 3 ppt, see Figure B13)

Forebay

phases c, a, b, c, a, b!, c!

- prior to the intake of water for the adjacent lock B the salinity in the forebay is measured twice in a long section (Figures B7 and B8); the salinity is about 1.5 – 2 ppt, but clearly a lower layer near the bottom is present with a higher salinity (up to about 4 ppt; smaller salinity values are found at greater distance to the lock)
- after withdrawal of water for levelling up lock B, the salinity and salinity ditribution in the forebay have almost not changed (Figure B10)
- after opening of the gates and subsequent passage of the ship salinity values in the forebay are, generally, a little higher; the lower layer near the floor with higher salinity has become thicker (salinity up to about 7 ppt, see Figure B11; note that position 1 is near to the closed 'normal' gates of lock B; these gates are located at the downstream side of the step in the floor, which explains the deep water at position 1); when the salinity is measured for the second time (after half an hour, no ship passages, Figure B12) the lower layer in the forebay with higher salinity has become thinner again, indicating that the water with higher salinity has intruded Miraflores Lake
- after the adjacent lock chamber B has filled for the second time, salinity and salinity distribution in the forebay are almost unchanged (Figure B14)
- after half an hour the upstream gates of Lock B are opened and salinities in the forebay are measured in a long section, starting from the open gates; the occurrence of a density flow is shown in Figure B15: a lower layer with higher salinity (of about 4 ppt) develops in upstream direction; the front of the corresponding reverse near-surface current with lower salinity was observed when it entered the lock (estimated propagation speed about 0.25 m/s).

Miraflores Locks, uplockage high tide

Measurements have been executed in Lock A, Lock B and the forebay. Results of measurements are presented in Figures B16 – B31.

Lock A

phases 2!, 3!, 3, 4

- after the ship has moved from the tailbay to Lock A and the gates are closed the salinity in the lower water region of the lock chamber is the same as in the forebay (33 – 34 ppt); near the water suface the salinity goes down to about 15 ppt (Figure B16)
- after the water in the lock chamber has levelled up with water from the adjacent lock B, the salinity at the downstream side of the lock is rather uniform in vertical direction, about 25 ppt, but salinity values near the floor are still higher (Figure B17)
- when the ship moves to lock B, water with lesser salinity enters the lock, comes up to the surface behind the ship and forms a top layer (Figure B18); the salinity goes down from about 25 ppt in the lower water region to about 5 ppt in the layer near the surface (Figure B19); internal waves occur

Lock B

phases 3, 4, 5, 2, 2!, 3!, 3, 4

- after the water in lock chamber B has levelled up with water from the forebay the salinity at the downstream side is more or less uniform, about 7.5 ppt; when the ship moves out, water with lesser salinity enters the chamber and the salinity decreases to about 5 ppt (Figure B20)
- after the gates have been closed, salinity is rather uniform in the vertical direction, but salinities at the upstream side are higher (variation in longitudinal direction from 5 ppt

to 7 ppt, Figure B21); probably the running propellor of the exiting ship causes some mixing

- after levelling down the salinity has decreased to an average value of about 5 ppt, while also gradients are present in vertical direction (Figure B22)
- when the next series of smaller vessels enters the lock chamber the salinity at the upstream side does not change initially, but after 10 minutes the salinity in the lower region has gone up from about 5 ppt to 15 – 20 ppt (Figure B23); these measurements indicate that density currents are likely to occur in the case of small ships (the saltier and heavier water is intruding over the upward step and along the floor; the return flow of the ships and the ships themselves are not sufficient to counteract or block the intruding flow)
- the next ship that enters lock B (after the series of smaller ships has left) causes similar phenomena as already discussed under 'Miraflores Locks, uplockage' (compare Figures B24 – B27 with Figures B1 – B4); however salinity levels in the lock chamber are generally higher, which may be caused by high tide conditions (at high tide more salt water is entering the lower lock A and this continues also to the higher lock B)

Forebay

phases c, a, b, c

- before water is taken in for the adjacent lock B the salinity in the forebay is about 1.5 ppt (Figure B28), but clearly a lower layer near the bottom is present with a higher salinity (up to 6 – 8 ppt); the water flowing towards the intake during withdrawal of water varies from 1.5 – 4.5 ppt (Figure B29)
- after withdrawal of fillwater, the salinity and salinity ditribution in the forebay have almost not changed (Figure B30)
- after opening of the gates and subsequent passage of the ship salinity values in the forebay are, generally, somewhat higher, in particular in the lower water region above the floor (Figure B31); this indicates that salt intrusion caused by density currents occurs during the exit of the ship.

Miraflores Locks, uplockage low tide

Measurements have been executed in the tailbay, Lock A and Lock B. Results of measurements are presented in Figures B32 – B39.

Tailbay

phases c, a, b

- salinities are measured in a long section in the tailbay prior to the release of spillwater from the adjacent lock A; salinity levels in the tailbay are high, about 33 ppt; a relatively thin top layer exists where the salinity goes down to about 22 ppt near the water surface (Figure B32)
- water that is released from Lock A during levelling down is withdrawn from the lower water region in the lock chamber with highest salinity; the salinity of the outflowing water measured at the water surface near the outlet varies about a value of 23 ppt (Figure B33)
- after water release but before entering of the ship in Lock A the salinities are again measured in a long section in the tailbay; it appears that the top layer with lesser salinity has thickened; the salinity in the top layer goes down to about 22 ppt near the water surface (Figure B34)

Lock A

phases 3, 4, 5

- after the water in Lock A has levelled up with water from the adjacent lock B, the salinity at the downstream side of the lock is rather uniform in vertical direction, about 21 ppt, but salinity values near the floor are higher (Figure B35); the hydraulic processes during and after exit of the ship are similar as described under 'Uplockage high tide' (compare Figures B18 / B19 with Figures B35 / B36), but salinity levels are generally somewhat lower (about 20 ppt in the water region near the floor, going down to about 5 ppt in the top layer near the water surface); lower salinity values may occur at low tide because a lesser quantity of salt enters the lock chamber; Figure B36 shows that internal waves occur in the lock chamber
- water is levelled down through openings in the floor; the withdrawal of water from the region near the floor does not strongly effect the salinity and salinity gradients in the remaining portion of the water (Figure B37)

Lock B

phase 2

- from Figure B39 it appears that lower salinity levels, which occur during low tide in Lock A, may also continue in Lock B (compare Figure B39 and B23)

Pedro Miguel Locks, uplockage

Measurements have been executed in the tailbay, Lock C and the forebay. The results of measurements are presented in Figures B40 – B54. These results should carefully be read, because the measured small salinity values have not been corrected for zero-salinity values (see Section 3.4). It means that presented values have to be reduced with 0.15 – 0.04 ppt, depending on the instrument that is used. In the next discussion we have corrections taken into account.

Tailbay

phases a, b, c

- the salinity of the spillwater that was released from Lock C (figure B40) was not well measured (the launch drifted away from the outlet)
- after release of water the salinity was measured in a long section of the tailbay (Figure B41); it appears that the salinity is realively small near to the gates, about 0.5 ppt; at a greater distance to the gates higher salinities are found, in particular near the bed, up to 1.5 – 2 ppt; when the ship has passed by and moved into the lock, a second quantity of water has come into the tailbay, but salinity levels and salinity gradients in the tailbay are still more or less the same (Figure B42)

Lock C

phases 3, 4, 5, 2, 2!, 3!,3, 4

- after the water has levelled up the salinity at the downstream side of Lock C is small and rather uniform (about 0.2 ppt) in vertical direction (Figure B43); this does not change much during exit of the ship
- after the ship has exited the salinity varies between 0.1 and 0.2 ppt throughout the entire chamber; some variation occurs in longitudinal direction but there are no important gradients in vertical direction (Figure B44)
- after the water has levelled down, salinities in the remaining water are more or less the same and some gradients are noticeable in vertical direction (Figure B45)
- more measurements with next ships (Figures B46 – B50) show that salinity levels may vary between nil to about 0.2 ppt, during the several phases of uplockage

Forebay

phases c, a, b, c

- after passage of the ship and prior to intake of water the salinity is measured in a long section of the tailbay; taking into account zero-salinity values (0.15 ppt) the salinity appears to be zero in the entire forebay (Figure B51)
- also measurements near the intake during withdrawal of water for levelling up Lock C, and measurements prior and after passage of the next ship show zero-salinity values (Figures B52 – B54)

Pedro Miguel Locks, downlockage

Measurements have been executed in the forebay, Lock C and the tailbay. The results of measurements are presented in Figures B55 – B64. Again, presented values have to be reduced with zero-salinity values of 0.15 – 0.04 ppt, depending on the instrument that is used. In the next discussion we have corrections taken into account.

Forebay

phase c

- salinity measurements are executed in long sections both in the western and eastern forebay after a long period of uplocking ships (Figures B55 and B56); taking into account zero-salinity values of 0.04 ppt the salinity varies from about 0.05 – 0.15 ppt near the gates to nil at some greater distance to the locks; vertical salinity gradients do almost not occur

Lock C

phases 2!, 3!,3, 4

- after a southbound ship has entered Lock C the salinity behind the ship (near upstream closed gates) is about 0.3 ppt (Figure B57)
- after levelling down and during exit of the ship the salinity of the remaining water in the lock chamber is still about 0.3 ppt near the upstream gates (Figures B58 and B59)
- when the ship has left and the downstream gates have been closed the salinity is in particular higher near the downstream gates (up to 0.7 ppt, Figure B60), indicating that water with higher salinity has entered the lock chamber during exit of the ship

Tailbay

phases c, a, b, c

- after passage of a southbound ship the salinity is measured in a long section in the tailbay (Figure B61); the salinity is more or less constant in the entire tailbay, about 1.4 ppt
- subsequently, spill water is released from Lock C; the salinity of the surface water near the outlet varies about a value of 1 ppt (Figure B62)
- after spillage, but before passage of a ship the salinity is measured in a long section in the tailbay (Figure B63); it appears that the salinity near the gates is reduced to about 1 ppt
- after passage of the ship (Figure B64) salinities tend to rise again, in particular at greater distance to the gates

Miraflores Locks, downlockage

Measurements have been executed in the forebay, Lock B and Lock A. Results of measurements are presented in Figures B65 – B72.

Forebay

phases c, a, b

- after passage of a southbound ship the salinity is measured in a long section in the forebay; the movement of the ship causes a density flow from Lock B into the forebay, this is shown in Figure B65; the salinity goes up to about 4 ppt in a layer near the bed, the salinity in the upper region is about 1.5 ppt
- after the ship has exited Lock B, the water in the lock chamber is levelled up again; water is taken in from the forebay; the salinity of the flow towards the intake varies between 1.5 and 3 ppt (Figure B66)
- after the intake of water, the salinity is measured in a long section in the forebay (Figure B67); the salinity is still about 1.5 ppt, but the layer near the bed with higher salinity has become thinner; this may indicate that a part of the saltier water is withdrawn during levelling up Lock B and / or that a part of the saltier water has intruded Miraflores Lake

Lock B

phases 3, 4, 5, 2

- after levelling down a strong salinity gradient exists at the upstream side of the lock chamber (at the stern of the big ship); when the ship exits, the salinity at the upstream side becomes more uniform in vertical direction (under the influence of return current and propellor action, Figure B68)
- subsequent measurements in a long section of the closed empty lock chamber show that density waves occur (Figure B69); the salinity in the upper portion of the water is about 4 ppt, the salinity in the region near the floor goes up to about 13 ppt
- after Lock B is filled with water from the forebay, the salinity has become almost uniform in the entire lock chamber (salinity 5 – 6 ppt, Figure B70), showing that the fill jets cause a lot of mixing
- when the next big ship enters Lock B the salinity of the upper portion of the water near the downstream side of the lock chamber reduces (Figures B71a/b, left and right side of the chamber); this shows that downlocking big ships may push water with lesser salinity into the lock chamber when they sail in

Lock A

phase 2

- when the same big ship enters lock A a similar but weaker phenomenon occurs near the downstream side of the lock chamber (Figure B72): in this case the reduction of salinity is mainly constraint to the region near the water surface; the overall salinity is about 17 ppt

Miraflores Locks, downlockage high tide

Measurements have been executed in Lock B, Lock A and the tailbay. Results of measurements are presented in Figures B73 – B81.

Lock B

phase 2

- upstream gates are kept open during a long period of time (> 20 minutes) to allow a group of small ships to enter; as a result water with lesser salinity enters Lock B; the salinity in the upper region of the lock chamber reduces to 1.5 – 2.5 ppt (Figure B73); clearly, density flows cause a considerable exchange of water when lock gates are kept open and ships are only small

Lock A

phases 2, 2!, 3!, 4

- the group of small ships enters Lock A; again, density differences cause a considerable exchange of water: the salinity in the upper water region near the downstream gates

reduces from about 12 to 1.5 ppt (Figure B74); the reduction in case of a big ship is much smaller (compare with Figure B72)

- after the group of small vessels has left Lock A and the water is levelled up, a big ship enters from Lock B; the salinity at the upstream side of the lock chamber (astern the vessel) is back at a value of about 17 ppt in the lower water region and decreases to 10 ppt near the water surface
- the water is levelled down; the salinity and salinity gradient of the remaining water at the downstream side of the lock chamber is unchanged after withdrawal of water (Figure B76); the spilled water may have a salinity between 17 and 25 ppt (Figure B80)
- when the big ship has exited Lock A and the gates have been closed strong salinity gradients are present in vertical and longitudinal direction (Figure B77); internal waves occur; salinities are up to 30 ppt in the region near the floor and go down to 12 ppt near the water surface

Tailbay

phases c, a, b, c

- prior to release of water from Lock A the salinity is measured twice in a long section of the tailbay; the salinity is about 33 ppt in the underlayer; the salinity goes down to about 25 ppt in the relatively thin top layer (Figures B78 and B79)
- during release of water from Lock A the salinity of the surface water near the outlet varies between 17 and 30 ppt (Figure B80); the spilled water may have a salinity between 17 and 25 ppt
- after the big ship has left Lock A and has passed the tailbay the salinity is measured in a long section of the tailbay (Figure B81); it appears that the movement of the ship does not cause important changes in the layered situation in the tailbay (compare with Figures B78 and B79)

Miraflores Locks, downlockage low tide

Measurements have been executed in Lock B, Lock A and the tailbay. Results of measurements are presented in Figures B82 – B97.

Lock B

phases 2!, 3!, 3, 4

- after a group of small ships and one bigger ship has entered Lock B the salinity is measured at the upstream side of the lock chamber (Figure B82); compared to 'downlockage high tide' (Figure B73) the salinity in the lower water region (about 6 ppt) seems somewhat smaller; compared to 'downlockage' (Figures B71a/b) the salinity in the lower water region of the lock seems more or less the same (note: it is not only the tide that may give differences, also ship dimensions and the duration of open gates have influence)
- after levelling down, the salinity distribution of the remaining water at the upstream side of the lock has not changed (withdrawal of water does not influence the salinity distribution, see Figure B83); when the ships move to Lock A the salinity at the upstream side of Lock B becomes more uniform, about 5 ppt, in vertical direction (effects of return currents and propellor action, Figure B84); simultaneously the salinity at the downstream side of Lock A is measured (Figure B93) see hereafter
- after the ships have exited Lock B and the gates have been closed, density waves occur in the lock chamber (Figure B85); the salinity is about 13 ppt near the floor and is about 5 ppt in the upper layer

Lock A

phases 3, 4, 5, 2, 2!, 3!, 4

- a group of smaller ships exits Lock A (Figure B90); the salinity at the upstream side of the lock chamber becomes more uniform during movement of the ship, about 13 ppt
- after the downstream gates have been closed the salinity is measured in a long section of the lock chamber (Figure B91); density waves occur; the salinity in the layer near the floor is about 32 ppt and goes down to about 10 ppt near the water surface; compared to 'downlockage high tide' (Figure B77) the underlayer with higher salinity is thinner, meaning that less salt water has intruded in the lock chamber
- after levelling up the salinity has become more uniform in the lock chamber (about 14 ppt, Figure B92)
- when the next group of vessels enters Lock A, some water with lesser salinity is pushed into the lock chamber ahead of the biggest ship (Figure B93)
- three hours later more salinity measurements are executed in Lock A; after a sailing yacht and a big vessel have entered the lock chamber a rather uniform salinity (about 16 ppt, Figure B86) is measured at the upstream side of the lock chamber; lowering of the water level does not change this salinity distribution (Figure B87)
- during exit of the ships salt water from the tailbay enters Lock A (Figure B88); after closure of the downstream gates density waves occur; the salinity is about 30 ppt near the floor and goes down to about 10 ppt near the water surface (Figure B89); more salt water has entered than during the earlier measurements, which were executed at lower tide

Tailbay

phases c, a, b, c

- salinity measurements have been executed in a long section of the tailbay prior to release of spill water from Lock A (Figure B94); the salinity in the underlayer is about 33 ppt, the salinity in the relatively thin toplayer goes down to about 25 ppt near the water surface
- during spillage of water from Lock A the salinity of the surface water near the outlet varies between 20 and 30 ppt (Figure B95)
- the salinity in the tailbay is measured immediately after the release of water from Lock A (Figure B96); it appears that the toplayer with lesser salinity has become thicker, in particular near the gates, and the salinity near the water surface has gone down to about 20 ppt
- after the sailing yacht and a big ship have left Lock A and has passed the tailbay the salinity is again measured in a long section of the tailbay (Figure B97); it appears that the movement of the ship does not cause important mixing effects in the tailbay (compare with Figure B96): the top layer still exists but the thickness of the layer is reduced; the latter is also caused by spreading of the layer in downstream direction

Gatun Locks (Locks D, E and F)

Tailbay Gatun Locks (Atlantic side)

Continuous salinity measurements with the CT-logger have been executed in the tailbay of Gatun Locks during about 5 consecutive days. The sensor was fixed at the outer edge of the wing wall in the eastern tailbay. The sensor was first positioned near the local bed and was than lifted to a position near the low-tide water surface. Results of these measurements are shown in Figure B138.

It appears that the temperature of the water is a little above 28 °C, both near the bed and near the water surface, similar as in the wet season. The salinity is about 32 ppt at the position near the bed and about 23 ppt in the higher position. Almost similar values were found during the wet-season measurements. Salinity fluctuations occur, but seem not to have a relation with the relative small tidal movements. Fast fluctuations can be ascribed to the continuous, but interrupted spillages from the locks. These spillages cause a top layer with lesser salinity, which continues in longitudinal direction of the sea entrance.

Gatun Locks, uplockage

Measurements have been executed in the tailbay, Lock D, Lock F and the forebay. Results of measurements are presented in Figures B98 – B111. Results of Lock F and the forebay should carefully be read, because the measured small salinity values have not been corrected for zero-salinity values (see Section 3.4). It means that presented values have to be reduced with 0.15 – 0.04 ppt, depending on the instrument that is used. In the next discussion we have corrections taken into account.

Tailbay

phases a, b, c

- release of spill water from Lock D (Figure B98): the surface salinity near the outlet varies between 15 and 22 ppt
- immediately after release of water the salinity is measured in a long section of the tailbay (Figure B99); the salinity in the underlayer is about 33 ppt; a rather thick top layer is present where the salinity goes down to 20 ppt at the water surface
- after passage of a southbound big ship and after the ship has entered Lock D the salinity is measured again in the tailbay (Figure B100); water from Lock D has entered the tailbay and it appears that the salinity in the forebay has generally reduced (salinity in underlayer about 30 ppt)

Lock D

phases 3, 4, 5

- salinities are measured at the downstream side of Lock D during exit of a big ship (Figure B101); initially - as a result of levelling up – the salinity is rather uniform in vertical direction (about 18 ppt), but when the ship moves from Lock D to the adjacent Lock E water with lesser salinity returns and causes a strong reduction of the salinity
- after the upstream gates have been closed strong gradients are present in vertical direction (salinity near floor about 18 ppt, near water surface about 7 ppt, see Figure B102), while also density waves occur in the empty lock chamber
- after levelling down the salinity and salinity gradients in the remaining water appear to be unchanged (Figure B103); the water in the region near the floor with highest salinity is withdrawn

Lock F

phases 2!, 3!,3, 4

- a big ship moves from the middle lock E to the upper lock F; after entry the salinity is measured at the downstream side of Lock F, astern the ship (Figure B 104); taking into account the zero-salinity correction the salinity is almost nil (0.2 ppt) at this location in the lock; the salinity does not change after the water in the lock chamber has levelled up with water from the forebay (Figure B105)
- when the ship exits Lock F, water from the forebay returns; the salinity at the downstream side of the lock chamber; varies about a value of 0.15 ppt but remains rather uniform in vertical direction (Figure B106)

- after the ship has left Lock F and the upstream gates have been closed, the salinity in the empty lock chamber varies in longitudinal direction between about nil and 0.15 ppt (Figure B107); salinities are clearly very small in the upper lock of Gatun Locks

Forebay

phases c, a, b, c

- salinities are measured in a long section of the forebay prior to the withdrawal of water (Figure B108), immediately after withdrawal of water (Figure B110) and after the southbound ship has exited the lock chamber and has passed the forebay (Figure B111); measured salinity values have to be corrected with 0.15 ppt; doing so salinities appear to be negligible in the forebay during all three phases
- also the salinity of the water near the intake during withdrawal of water has zero salinity (Figure B109)

Gatun Locks, downlockage

Measurements have been executed in the forebay, Lock , Lock D and the tailbay. Results of measurements are presented in Figures B112 – B128. Again, results of Lock F and the forebay should carefully be read, because the measured small salinity values have not been corrected for zero-salinity values (see Section 3.4). In the next discussion corrections have been taken into account.

Forebay

phases c, a, b, c

- salinities are measured in a long section of the forebay after passage of a northbound ship and prior to the withdrawal of water (Figure B112); measured salinity values have to be corrected with 0.04 ppt; doing so salinities appear to vary in longitudinal direction between about 0.1 ppt near the gates till zero at some greater distance to the gates
- subsequently, after the ship has moved from the upper lock F to the middle lock E, the water in Lock F is levelled up again; the salinity of the water near the intake during withdrawal of water from the forebay is measured (Figure B113); after correction the salinity appears to be zero, but near the floor a salinity up to about 0.08 ppt is found
- immediately after withdrawal of water salinities are measured in a long section of the forebay (Figure B114); after correction of the measured salinity values it appears that small salinities up to about 0.08 ppt are present in the deeper region near the bed
- when a next vessel has passed the forebay and has entered the upper lock F, water from the lock has returned into the tailbay and salinities near the gates have gone up to about 0.15 ppt (correction taken into account); the salinity reduces with a greater distance to the locks to zero (Figure B115)

Lock F

phases 3, 4, 5 ,2

- measurements are executed at the upstream side of Lock F during the exit of a big ship and inflow of return water from Lock E (Figure B116); the salinity remains more or less constant during exit and uniform in the vertical direction, about 0.15 ppt after correction
- after the ship has exited, salinities are measured in a long section of the empty lock chamber (Figure B117); clearly salinity gradients are present in vertical and longitudinal direction; salinity values range between 0.15 and 0.8 ppt (after correction)
- after the water has levelled up salinities are more or less uniform in the entire lock chamber, about 0.25 ppt (after correction), see Figure B118; again, filling jets which rise up from openings in the floor, appear to mix up the water considerably

- the next big vessel enters from the forebay into Lock F; the salinity is measured near the downstream side of the lock chamber ahead of the ship (Figure B119); the salinity is uniform in vertical direction and remains constant, about 0.25 ppt (after correction) during entering of the ship

Lock D

phases 2, 2!,3!, 3, 4

- measurements are executed at the downstream side of Lock D during entering of a big vessel (Figure B120); initially the salinity is uniform in vertical direction (salinity about 14 ppt) caused by filling the lock chamber; than water with lower salinity reaches the downstream side; this water may be pushed in by the moving vessel but may also be the result of density flows which occur after opening of the gates; the salinity near the water surface reduces to about 4 ppt
- when a next big vessel enters Lock D and upstream gates have been closed, the salinity is measured at the upstream side of the lock chamber, astern the ship (Figure B121); at this location the salinity is about 14 ppt, but reduces to about 10 ppt going up to the water surface
- the water in Lock D is levelled down; after levelling down the salinity is still about 14 ppt at the upstream side of the lock chamber, astern the ship, with some reduction towards the water level (Figure B122); during the subsequent exit of the vessel into the tailbay saltier water enters the lock chamber over the flat floor (no step) and salinities near the floor at the upstream end go up to about 25 ppt (Figure B123)
- after the downstream gates have been closed density waves occur in the empty lock chamber (Figure B124); salinities vary in vertical and longitudinal direction (from about 12 ppt near the water surface till about 28 ppt near the floor)

Tailbay

phases c, a, b, c

- prior to release of spill water from Lock D the salinity is measured in a long section in the tailbay (Figure B125); the salinity in the underlayer is about 33 ppt and goes down in the top layer near the water surface to about 22 ppt
- the salinity of the surface-water beside the outlet varies about a value of 20 ppt during release of water (Figure B126)
- immediately after release of water from Lock D the salinity is measured in a long section of the tailbay (Figure 127); near to the gates the top layer with lesser salinity has become thicker; this layer spreads in downstream direction
- after the ship has exited Lock D and has passed the tailbay the salinity is again measured in a long section of the tailbay (Figure B128); it appears that the salinity near the locks has become more uniform in vertical direction; this mixing effect is less at a greater distance to the locks (salinity of underlayer still 33 ppt)

Miraflores Lake, Gaillard Cut and Gatun Lake

Miraflores Lake

Selected results of salinity measurements in Miraflores Lake are presented in Figures B129 – B131.

Salinity profiles have been measured in a longitudinal section in the shipping channel from Miraflores Locks to Pedro Miguel Locks (Figure B131), and in sections parallel and perpendicular to Miraflores Spillway (Figures B129 and B130).

Measurements in the shipping lane show that the salinity is about 1.3 ppt at the water surface near Miraflores Locks, going down to about 1.0 ppt near Pedro Miguel Locks. In the water region above the bed salinity values are higher; they vary roughly between 2.0 ppt and 3.5 ppt in the entire channel.
Detailed measurements in sections near Miraflores Spillway show salinity values between about 1.2 ppt near the water surface and 1.5 – 2.5 ppt near the bed. The latter values are somewhat smaller than the values found near the bed in the shipping channel (see also Section 4.2.3).

Compared to the salinity levels measured in Miraflores Lake in the wet season, salinities in the dry season have become about two or three times as high.

Gaillard Cut and Gatun Lake

Selected results of salinity measurements in Gaillard Cut and Gatun Lake are presented in Figures B132 – B136.

Salinity measurements have been executed in a longitudinal section in the shipping channel of Gaillard Cut, from Pedro Miguel Locks to Gamboa (Figures B132 – B133). Vertical salinity profiles were taken at regular mutual distances. The measured salinity values shown in Figure B132 have to be corrected with about 0.15 ppt (see Section 3.4), the values shown in Figure B133 with about 0.02 ppt. Doing so, the salinity appears to be nil or almost zero in the entire channel.
Vertical salinity profiles were also taken in the deeper area east of Gatun Locks, where ships are berthing. In this area profilings were done in a longitudinal section along the east bank of the lake (Figure B136). Salinity values appear to be zero or almost zero (after correction). In the area near to the locks salinity values are up to about 0.02 ppt
Salinity profiles were also measured in the deep area near Gatun Spillway. Profiling was done in a longitudinal section from Gatun Locks along the west bank to the area near the spillway and back around the island (Figures B134 and B135). The measured salinity values have to be corrected with about 0.12 ppt (see Section 3.4); after correction salinity values appear to be zero in the greater part of the area; only in the immediate surroundings of the Gatun Locks salinities up to about 0.04 ppt are found and occasionally 0.08 ppt near the bed.

The results of these salinity measurements in Gatun Lake and Gaillard Cut are more or less similar to those which were obtained in the wet-season measurement campaign. Measured salinity values are nil in the greater part of Gatun Lake; only in the area near to the locks small salinity values are found. The applied CTD's have a lower measurement limit of 0.1 ‰ salinity; this makes salinity measurements below a value of 0.1 ppt unreliable. A safe conclusion is therefore that the salt concentration of Gatun Lake and Gaillard Cut was smaller than 0.1 ppt during the measurements in the dry season.

3.6 Range of salinity values in basins

The salinity measurements show that average salinity levels decrease considerably going from the sea entrances to Miraflores Lake and Gatun Lake. Layering and density waves are normal hydraulic phenomena in closed lock chambers, while density currents between

adjacent basins occur when gates are open. Next Table 3.4, which is based on the results of our measurements, presents an approximate range of *volume-averaged* salinity values in the various basins. Since our measurements represent only a few moments in time, the full range of salt concentrations may be broader. Local salt concentrations in the lakes may be higher than the volume-averaged salt concentrations, in particular near the bed in forebays of the locks, shipping channels and (deeper) areas near the spillways. Volume-averaged salt concentrations in lock chambers are shown for high and low water level (no ship in lock chamber); a distinction is made between uplockage and downlockage. Generally, salt concentrations near the floor of the lock chambers are higher than near the water surface.
The results of the salinity measurements executed in the past (Section 2.3) are broadly in line with the present measurement results.

Basin	*Outside locks*	*Locks, uplockage*			*Locks, downlockage*	
		low	high	low	low	high
		phase 1	phase 4	phase 5	phase 4	phase 5
Tailbay Miraflores Locks	25-34					
Lock A		20-28	7-18	5-16	10-25	6-15
Lock B			1-7	1-5	1-10	1-6
Forebay Miraflores Locks	1.0-2.5					
Miraflores Lake	0.7-1.5					
Tailbay Pedro Miguel Locks	0.5-1.5					
Lock C			0.1-0.3	0.1-0.2	0.2-1.0	0.1-0.5
Forebay Pedro Miguel Locks	< 0.1					
Gatun Lake	< 0.1					
Forebay Gatun Locks	< 0.1					
Lock F			0.1-0.3	0.1-0.2	0.2-2.5	0.1-1.5
Lock E			1-7	1-5	1-10	1-6
Lock D		24-27	7-18	5-16	10-25	6-15
Tailbay Gatun Locks	28-32					

Table 3.4 Approximate range of volume-averaged salinity levels (ppt or g/l) in various basins of the Panama Canal system

4 Qualitative interpretation of salt water intrusion in existing situation

4.1 Pacific Entrance and Atlantic Entrance

Miraflores Locks at the Pacific side of the canal are situated at the end of a long entrance channel, which starts some kilometers out of the shoreline. The Amador Causeway, a dam between small islands near the coast and the shore, screens the entrance from currents and waves. The tide variation is considerably: 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. As a result strong tidal currents occur in the channel up to Miraflores Locks, but near the locks the tidal movement is a vertical movement rather than a horizontal movement.

Gatun Locks at the Atlantic side of the canal are also located at the end of a long entrance channel. The entrance is protected against waves by breakwaters. The tide variation is only small: the sea level near Colon varies between the extremes PLD -0.38 m and PLD +0.56 m, mean sea level PLD +0.06 m.

Water temperatures, conductivities (salinities) and depth were measured in the entire canal system. In the wet season (measurements in November – December 2001) the water temperature appeared to be almost constant throughout the entire canal system (Pacific tailbay, Miraflores Locks, Miraflores Lake, Pedro Miguel Locks, Gaillard Cut. Gatun Lake, Gatun Locks, Atlantic tailbay). Temperatures varied roughly between 27.5 and 28.5 °C, and because of the constant value, temperature was not a relevant influencing factor for density currents.
Measurements in the dry season (April 2002) showed that the water temperature in the Pacific Entrance near Miraflores Locks was much lower than in the wet season: about 21 °C (versus 28 °C in the wet season), while the temperature in the Atlantic Entrance was still the same (about 28 °C). Consequently, there were also lower temperatures in Miraflores Locks going up from 22 °C in the lower locks (Lock A) to about 28 °C in the forebay in Miraflores Lake. The temperature in Miraflores Lake, Pedro Miguel Locks, Gaillard Cut, Gatun Lake and Gatun Locks appeared to have a more or less constant value of about 28 °C. Both a higher salinity and a lower temperature cause a higher density and will thus have caused stronger density currents and exchange flows between tailbay and lower Lock A, between lock A and Lock B and between Lock B and the forebay in Miraflores Lake.

4.1.1 Pacific Entrance

Measurements in the wet season show that an underlayer exists in the entrance with a constant salinity; the salinity is about 28 ppt near the locks. Spillages from the locks cause lower salinity values in a layer near the water surface. The thickness of this upper layer, where the salinity may reduce considerably in the area near the locks, depends mainly on the number of lockages (quantity of spilled water) and on pauses between lockage periods (the intermittent spill flow may be stopped during several hours). The tidal variation (incoming

tide or falling tide) seems not to be very important for the salinity levels in the area near to the locks. It is true that the tidal movement causes an inflow and outflow of water in the sea entrance, but horizontal tidal flow velocities near the locks are small and do not cause an important mixing up. As a result, only the thickness of the lower layer where the salinity has a more or less constant value of about 28 ppt varies with the tidal movement. The temperature in this underlayer is about 28 °C. The upper layer with lesser salinity, which is caused by the spillages from the locks, is moving up and down with the thickness variation of the underlayer, but is not mixing up with the underlayer.
Measurements in the dry season show that the temperature in the underlayer is considerably lower, about 21 °C, while the salinity is higher, about 34 ppt. Possibly, these differences are caused by seasonal variations in the flows towards the Pacific coast.

The measurements do not show that the spill flows with lower salinity propagate as more or less concentrated density flows along west or east bank of the tailbay. It appears that the water with lower salinity spreads in the tailbay. This can be concluded from measurements in the centre line of the approach wall, where the salinity in the upper water region is similar as at locations near to the banks.

4.1.2 Atlantic Entrance

Measurements in the Pacific Entrance show that an underlayer exists, similar as in the Pacific Entrance, where the salinity and temperature are constant. In the wet season the salinity in the underlayer near the locks was about 31 ppt, in the dry season a little higher about 32 ppt. The temperature of the water in the underlayer was more or less constant, about 28 °C. The thickness and the salinity of the top layer vary in dependence of the distance to the locks. Salinity fluctuations in the top layer are caused by the continuous, but interrupted spill flows from Gatun Locks.

4.2 Salt water intrusion process in locks

Extensive measurements have been executed in the locks, forebays and tailbays. From the analysis of the measurement data and visual observations some characteristic hydraulic processes have been identified with respect to the intrusion of salt water during uplockage and downlockage of ships. These characteristic processes are described hereafter. General conclusions based on the salinity measurements are: (i) important transverse density phenomena do not occur in the lock chambers, (ii) average salinity levels decrease considerably in each higher lock chamber, and (iii) a more or less cyclic pattern of salt water intrusion may be expected, which is caused by alternate periods of uplockage and downlockage of ships.

4.2.1 Hydraulic processes in locks during uplockage

The following characteristic hydraulic processes have been identified during uplockage:

Low water level in lock chamber, downstream gates are opened
Density differences between the water in the lock chamber and the water in the adjacent lower tailbay or lock cause density flows; a salt tongue is intruding along the floor of the

lock chamber and simultaneously water with lesser density and lesser salinity is flowing out in the upper region of the water.
In the lower locks adjacent to the sea entrances an almost full exchange with salt water from the tailbays is possible, in particular at the Pacific side, where present operation rules prescribe that gates are opened immediately after levelling down, far before the next ship arrives. The longer the downstream gates are open before the ship enters, the more the exchange process proceeds and the more the upper layer with lesser salinity reduces; however, a full replacement with salt water from the tailbay is not reached, a thin top layer with lesser salinity remains. It may take about 0.5 hour to arrive at this situation; the corresponding velocity of the density current fronts may vary between 0.5 and 1.0 m/s.
In middle locks or upper locks the intruding density currents have to pass the upward step in the floor; this step forms an effective obstacle for salt water intrusion. Probably only the saltier water in the region above the level of the step is involved in the salt intrusion process. In upper locks density flow phenomena are very weak.

Vessel enters lock chamber, downstream gates are closed
The vessel enters the lock chamber. Doing so it pushes the water at the bow foreward (big ships cause a translatory wave in the lock chamber), but simultaneously the return current along the ship hull transports water from the area at the bow of the ship to the stern. The return current may partly or fully prevent a further intrusion of salt water along the floor of the lock (this counter-acting effect is stronger in the case of a big ship with large draught and beam). The dimensions of the vessel are thus strongly determinative for the extent of the exchange flows: at least the submerged volume of the vessel is exchanged. Also the period that gates are kept open has influence.
When the vessel enters a lower lock adjacent to the sea entrance, the situation with high tide is unfavourable since the ample space under the ship causes a less effective counter-acting return flow. At low tide the return current is stronger and may be more effective. However, when the gates were open during a longer period of time the salt intrusion process might already have been completed prior to entry of the ship.
When the vessel enters a middle lock or an upper lock it passes over the upward step in the floor; return currents become stronger because of the smaller space under the ship and may also be more effective in the prevention of a further intrusion of the saltier water.
After the gates are closed the salt water intrusion stops; internal density waves may still occur along the ship in the closed lock chamber.

Water in lock chamber is levelled up
The lock chamber is filled through the openings in the floor with water from the adjacent higher lock or lake, which is generally less saline. The jets cause a strong turbulence and the water in the lock chamber is mixed up. Measurements show that the salinity in the lock is more or less uniform at the end of the filling process.
The water is drawn from the lower region of the adjacent higher lock or from the area of the forebay near the intakes. This water contains salt and in this way salt water is sluiced back. However, in general the average salinity level in the lock chamber is reduced after filling. High tide in the sea entrance causes a high water level in the lower lock; consequently a lesser quantity of fill water is required to level up. The reduction of the salinity level in the lock chamber after filling will therefore be smaller in the case of high tide than in the case of low tide (this observation holds in particular for the Pacific side where large tidal amplitudes are normal). The effect of the tide is also perceptible in higher locks, but is weaker there.

High water level in lock chamber, upstream gates are opened, vessel exits
After the upstream gates of the lock chamber have been opened density currents develop between the water in the lock chamber and the adjacent higher lock chamber or lake. Water with a higher salt concentration migrates over the upward step in the floor into the adjacent higher lock or lake, whereas water with a lesser salinity returns. The exchange of water is mainly in the water region above the level of the upward step; most probably, the step prevents the water in the lower region of the lock chamber to escape. The water exchange depends on the density difference, but also on the time till the start of movement of the vessel, and the position and dimensions of the vessel.
The moving vessel pushes water at the bow of the ship and causes a return current, which may counteract the migration of saltier water to the adjacent higher lock or lake. The bigger the ship, the stronger and the more effective the return current. The quantity of water that is exchanged with the adjacent higher lock or lake is thus strongly dependent on the dimensions of the ship. At least the full submerged volume of the ship is replaced with water from the adjacent higher basin; this water has generally a lower salinity. In the case of small ships return currents are weaker and density flows may fully develop, causing more intrusion of saltier water.
The running propellor causes mixing in the water area near the stern of the ship. The more power is applied the stronger the mixing.

Upstream gates are closed, water in lock chamber is levelled down
After the ship has sailed away and the upstream gates have been closed, salinity gradients in vertical direction indicate that a more or less layered system has established in the lock chamber. Internal density waves are present which dampen only very slowly.
Subsequently, the water is levelled down. The withdrawal of water does not strongly effect the salinity gradient in the remaining upper portion of the water; water is mainly drawn from the lower water region with highest salinity and is spilled in the adjacent lower lock or tailbay.

4.2.2 Hydraulic processes in locks during downlockage

The characteristic hydraulic processes during downlockage of vessels, which were observed during execution of the measurements and which appear from the analysis of measurement data, are as follows:

High water level in lock chamber, upstream gates are opened
Density differences cause an exchange of water between the lock chamber and the adjacent higher lock or forebay. The water in the lock chamber was earlier mixed up during the filling process; this resulted in a rather uniform salinity throughout the empty lock chamber. The exchange flows occur mainly in the upper water region of the lock above the level of the downward step in the floor. Water with a higher salt concentration creeps over the step in the floor in upstream direction, while water with a lower salt concentration enters the lock chamber near the water surface. The amount of exchanged water depends on the time during which the gates are open. Layering may occur in the lock chamber. When no ship enters, the upper portion of the water in the lock chamber may for the greater part be exchanged with water from the forebay. However, for the upper locks of Gatun Locks and for Pedro Miguel Locks it holds that density differences between forebay and lock chamber are usually very small; consequently density currents, if any, are weak.

Vessel enters lock chamber, upstream gates are closed

During entering the water at the bow of the ship is pushed (big ships cause considerable translatory waves, which may even overtop the downstream gates), but simultaneously the return current transports water from the lock chamber to the adjacent higher lock or forebay. This water is generally more saline. In the case of small ships return currents are weaker and density flows may fully develop. The total amount of outflowing water is thus depending on the dimensions of the vessel, but also the period that gates are open plays a role; at least the submerged volume of the ship is exchanged.

After the ship has entered salinity gradients in vertical direction, corresponding with the inflow of less saline water from the adjacent higher lock or forebay, may be present in the lock chamber.

Water in lock chamber is levelled down

The water is sluiced through the openings in the floor. The water is mainly drawn from the lower, saltier water region of the lock chamber. Initially there is an ample space under the ship; when levelling down proceeds this space becomes narrower, and the flow towards the sluice openings is more in a horizontal plane, but is also decreasing. The drained water contains salt and in this way salt water is sluiced back to the adjacent lower lock or tailbay. In general, the average salinity in the lock chamber will be smaller after levelling down.

In the case of high tide in the adjacent sea entrance a lesser quantity of water is spilled from the lock chamber than at low tide. The reduction of the salinity level in the lock chamber after levelling down will, therefore, be somewhat smaller in the case of high tide than in the case of low tide (in particular valid for the Pacific side where large tidal amplitudes occur). The effect of the tide is also perceptible in higher locks, but becomes weaker and less markedly at each higher lock.

The salinity gradients in the upper portion of the water in the lock chamber remain more or less intact during the lowering of the water level in the lock. The water with lesser salinity remains on top of the more saline water.

The water is spilled through openings in the floor of the adjacent lower lock, where it mixes with the receiving water, or is spilled as a concentrated flow in the tailbay.

Low water level in lock chamber, downstream gates are opened, vessel exits

After the water in the lock chamber has levelled down and the downstream gates are opened, density currents develop between the water in the lock chamber and the adjacent lower lock or tailbay.

In the case of a lock at the downstream side the earlier spilled water has mixed up with the water that was already present in the lock. This has resulted in a more or less uniform salinity in the lower lock, but this salinity is generally higher than the salinity in the lock chamber under consideration. The water with higher salinity enters the lock chamber over the downward step in the floor and water with lesser salinity flows out at the water surface. The exchange of water is mainly in the water region above the level of the step; most probably, the step prevents the water in the lower region of the lower lock to intrude.

When a tailbay is present at the downstream side the earlier spilled water (which has been released in the form of a concentrated outflow) proceeds in the tailbay as a surface layer on top of the salt water. At high tide a lesser quantity of water is spilled than at low tide. The effect on the salinity in the tailbay will, therefore, be less at high tide. The density flows between lock chamber and tailbay after opening of the gates develop initially over the full water depth (no downward step). Bigger ships may form an obstacle for the density flows.

At high tide more space is available under the ship in the lock chamber and stronger density flows may occur.
The quantity of exchanged water depends on the density difference, but also on the time till the start of movement of the vessel, and the position and dimensions of the vessel.
The exit of the ship causes an inflow of water from the adjacent lower lock or tailbay, which has generally a higher salinity. Some layering occurs. Water at the stern of the ship is partly mixed up because of the propellor action.

Downstream gates are closed, water in lock chamber is levelled up
After the ship has sailed away and the downstream gates have been closed salinity gradients are present in vertical direction which indicate a more or less layered water system. Internal density waves occur in longitudinal direction of the lock chamber; these waves die out only very slowly.
The lock chamber is filled with water from the adjacent higher lock or forebay through the openings in the floor. This water has, generally, a lower salt concentration than the water that is already present in the lock. The jets come up to the water surface and spread over the lock chamber area. The measurements show that the salinity in the lock chamber is more or less uniform in the entire water volume at the end of the filling process. This is caused by the heavy turbulence which is generated by the filling jets.

4.2.3 Differences between uplockage and downlockage

There are several apparent differences between uplockage and downlockage. Key notions are: an upward movement of the ship goes together with a downward movement of water, a downward movement of the ship goes together with an upward movement of water; fill water is always going downward; fill water dilutes, and fill jets mix up the water in a lower lock chamber; the step in the floor at the upstream side of the lock chambers influences the currents driven by density differences, and limits the salt water intrusion.

Uplockage
The uplockage process starts in a lower lock, that for the greater part is filled with saline seawater; this holds in particular for the locks at the Pacific side where lock gates are opened far before the ship arrives. When the ship enters, a quantity of water equal to the submerged volume of the ship is pushed away and flows out to the seaside tailbay. Due to density effects and the movement of the ship an additional exchange of water between the lock and the seaside tailbay occurs: water with lesser salinity moves to the seaside tailbay and is replaced by an almost equal quantity of water with higher salinity, causing salt water intrusion. This process repeats in each higher lock, but the upward step at the entrance of a higher lock together with the return current along the ship are effective means to limit the salt water intrusion. Moreover, fill water from the higher adjacent lock is drawn from the water region near to the floor, which has the highest salinity, or from the forebay. In this way salt water will be sluiced back. A disadvantage of the floor filling system is that the filling jets mix up the entire water volume around the ship in a lock chamber; in view of a prevention of salt water intrusion to the adjacent higher basin this is unfavourable.

Downlockage
The adverse effect of the filling jets is especially clear during downlockage of a ship. Starting with the upper lock (no ship in the lock chamber), water is filled from the forebay. A part of the earlier intruded salt is drained back with the fill water. The water in the lock

chamber is diluted by the supply of this water that, generally, has a lesser salinity than the receiving water in the lock chamber. However, the filling jets mix up the entire water body. As a result higher salt concentrations are also present in the upper part of the water body, near the water surface. When the ship enters, a water quantity equal to the submerged volume of the ship is pushed away and flows back to the forebay. This water has it's origine mainly in the upper region of the water in the lock chamber, and because of the intensive mixing process it contains salt. Density differences and the movement of the ship cause an additional exchange of water between the lock chamber and the forebay. In this situation the downward step at the entrance to the lock chamber is less effective in the prevention or reduction of salt water intrusion. This process repeats in each next lower lock. The tide in the sea entrance is in particular of importance for the last phase in the downlockage process, when the ship enters the lower lock adjacent to the seaside tailbay. At high tide the water level in this lock is high and consequently only a relatively small quantity of fill water is required to level up. The water in the lower lock is thus less diluted, and water with a higher salt concentration intrudes in the adjacent higher lock. Contrary, low tide in the sea entrance causes a lesser salt intrusion.

Generally spoken, more salt is transported in upstream direction during downlockage than during uplockage. Possibly, in some cases even a negative transport may occur during uplockage. High tide is more unfavourable for salt intrusion than low tide, both at uplockage and downlockage. Bigger ships cause a greater return current and are thus unfavourable in the case of downlockage; smaller ships cause a lesser return current but because of that the development of density flows is less hampered, and becomes mainly a function of time. Smaller ships come in groups, and require more time for operation. As a consequence, gates may be open during a longer period of time, which is unfavourable in view of a prevention of salt water intrusion.

4.3 Salt water intrusion in Miraflores Lake and Gatun Lake

4.3.1 Miraflores Lake

Lockage operations at Pedro Miguel are the reason that Miraflores Lake is fed with a more or less continous spill flow from Gatun Lake. Rainwater enters at several locations along the west and east bank. Evaporation and lockage operations at Miraflores cause water losses. The drain water quantity at Miraflores Locks is somewhat smaller than at Pedro Miguel Locks. Surplus water is spilled through the spillway beside Miraflores Locks. This is also the location where water is drawn for cooling water purposes. As a result a flow circulation pattern exists with a net flux in southern direction towards Miraflores. In the dry season water supply is for the greater part caused by lockage operations at Pedro Miguel. The water level in Miraflores Lake is maintained at about PLD +54.5 ft (PLD +16.6 m) throughout the year.

Salinity profiles have been measured in the wet season in the shipping channel from Miraflores Locks to Pedro Miguel Locks, along west and east bank of Miraflores Lake, and in the area near Miraflores Spillway. In the dry season measurements were repeated in the shipping channel and near Miraflores Spillway.

Measurements in the wet season show that the depth-averaged salinity is about 0.5 ppt in the entire channel between Miraflores Locks and Pedro Miguel Locks, but near the bed salinity values are up to about 1.5 ppt (smaller values up to about 1.0 ppt are found near Pedro Miguel Locks, while salinity values near the water surface may be smaller than 0.5 ppt).
Detailed measurements in sections near Miraflores Spillway (spillway not active) show salinity values between about 0.3 ppt near the water surface and 0.8 ppt near the bed.

Measurements in the dry season in the shipping channel show that the salinity is about 1.3 ppt near the water surface in the area of Miraflores Locks, going down to about 1.0 ppt near Pedro Miguel Locks. In the water region above the bed salinity values are higher; they vary roughly between 2.0 ppt and 3.5 ppt in the entire channel.
Measurements in the area near Miraflores Spillway (spillway not active) show salinity values between about 1.2 ppt near the water surface and 1.5 – 2.5 ppt near the bed.

The salinity values which are found near the bed in the area near the spillway are generally smaller than the values found near the bed in the shipping channel. This may indicate that the salt water, intruded through Miraflores Locks, initially propagates in the deeper area of the shipping channel. It is than subjected to a diffusion process and finally flows with the dominant stream pattern to the spillway. However, in periods that the spillway of Miraflores is active a part of the salt water from Miraflores Locks may also directly flow to the spillway.

When wet-season and dry-season results are compared it appears that the salinity in Miraflores Lake has become higher in the period between the two measurement campaigns. Probably, the higher salinity in the dry season is a seasonal effect caused by a lesser release of surplus water at Miraflores Spillway. Also the lower temperature and the higher salinity of the water in the Pacific Entrance in the dry season will play a role, because the temperature difference between Miraflores Lake and the sea entrance and the greater salinity difference cause stronger density currents and exchange flows, and thus a greater inflow of salt water.

4.3.2 Gaillard Cut and Gatun Lake

Gatun Lake receives water from Chagres River (Madden Lake) and other rivers. Lockage operations at Pedro Miguel and Gatun and evaporation cause a loss of water. Surplus water is spilled at Gatun Spillway; water is also drawn at this location for power generation. The water circulation pattern is towards Pedro Miguel Locks in the southern part of Gaillard Cut and towards Gatun Locks and Gatun Spillway in Gatun Lake.

Salinity measurements have been executed in the wet season in the entire shipping channel from Gatun Locks to Pedro Miguel Locks. Vertical salinity profiles were also taken in the deeper area east of Gatun Locks, where ships berth, and in the deeper area near Gatun Dam and Gatun Spillway. A part of these measurements was repeated in the dry season.

The salinity measurements show that the salinity is zero in the entire channel and in the deeper areas near east bank and Gatun Spillway. Only in the areas near to Gatun Locks and Pedro Miguel Locks small salinity values are found; occasionally values up to about 0.1 ppt are found in the forebays near the bed. Considering also the lower measurement limit of the CTD's of 0.1 ‰ salinity, which makes salinity measurements below a value of 0.1 ppt

unreliable, the conclusion is that salinity levels in Gatun Lake and Gaillard Cut are lower than 0.1 ppt. Note that the fresh-water limit is defined by 0.20 – 0.25 ppt cloridity, which corresponds to 0.4 – 0.5 ppt salinity.

There is no indication that salinity values of Gatun Lake are higher in the dry season, when the water level is lower. Salinity measurements which were executed in Gatun Lake and Gaillard Cut in wet and dry season gave more or less similar results. It should, however, be noted that the water level in Gatun Lake during the dry-season measurements was only 0.5 m lower than in the wet season. Usually, the water level decreases with about 1 m. A lower water level causes a lesser quantity of drain water; this is, generally, less favourable in view of a prevention of salt water intrusion.

5 Simulation model

The salt water intrusion process through the locks on the Panama Canal is simulated with a numerical model. This model has been developed after the execution and analysis of the wet season salinity measurements. 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. The design of the model is described in next sections.

The simulation model has been set up to predict 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. The 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. This 3d-flow model may use the salt water load caused by the operation of existing and Post-Panamax Locks as input.

5.1 Concept

The entrances of the Panama Canal at the Pacific and Atlantic side are hydraulically connected to Miraflores Lake and Gatun Lake through the locks on the canal. 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 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.
The simulation model 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).

In the present canal system there are two shipping lanes, each having similar locks. Lock chambers are filled or emptied through the main culverts in side walls and centre wall of the locks. Fill water is sluiced from forebay to lock chamber, from lock chamber to lock chamber, and finally spilled in the seaside tailbays; in the case of an excess of water in one of the lock chambers water may be discharged directly from a higher chamber to the seaside tailbays. The chambers of the locks in west and east shipping lane are hydraulically connected, but exchange of water between lock chambers in the two lanes is not practised in normal operation of the locks. The separate basins of the Panama Canal (lock chambers, 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 5.1. In the future a new lane may be opened with locks suited for Post-Panamax vessels. In the present study the 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, the 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.

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. 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.

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. To that purpose a lineair function of time is applied in the simulation model. After a certain period 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 in the simulation model 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.

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. Spillage of surplus water or supply of additional water may than be necessary. Since exceedance of maximum or minimum water level in a lock chamber is rare, and the quantity of spilled surplus water or supplied additional water is relatively small, accurate computation of the effect of these operations on the salt concentration in the lock chambers is not needed. For this reason the assumption is made that spillage of excess water or supply of additional water will not influence the salt conconcentration in the lock chamber (the spilled or supplied water quantity has an equal salt concentration as the water in the node where it is spilled from or supplied to).
When gates are removed for maintenance purposes or are otherwise out of use, other gates of the locks may be used. Consequently, the length of adjacent lock chambers will deviate from the normal chamber length. Though the dimensions of the lock chambers can be adapted in the simulation model, temporarily smaller or greater lengths of lock chambers are not taken into account in the simulations, because, in the long run, they don't have a relevant effect on the salt concentration in the lakes.

The subsequent steps of a ship movement are described in a scenario together with other data relevant to that ship movement, namely shipping lane, water displacement of the ship, and duration of the ship movement. Special scenarios are scenarios that describe a 'turn around' (change from northbound ship transits to southbound ship transits or reverse) and water releases (water releases at Gatun Dam and Miraflores Dam).

Scenarios are combined in a day pattern. The start time of each scenario is prescribed in the daypattern. 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 5.3). A case contains information on start and stop date of the simulation. Day patterns are handled one by one in the sequence of input. After handling of the last day pattern 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 Section 5.8) and define initial values (dimensions of locks etc., water levels, water volumes and salt concentrations). The set of exchange coefficients and the intial values form a part of the case.

At the start of each case nodal status parameters are initialized (see Section 5.7). 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 5.2.

5.2 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.

5.2.1 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 or g/l; 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.

5.2.2 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)
floor level or sill level:	f (in m to PLD)
time:	t (date, hour)

5.2.3 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)

5.2.4 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)

5.2.5 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)

5.2.6 Status parameters and other parameters of existing 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)
min. water level: $minh_{lock}$ (input)
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)

5.3 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. The subsequent steps of a ship movement are described in a scenario together with other data relevant to that ship movement, namely shipping lane, water displacement S of the ship, and duration of the ship movement. The start of a scenario is prescribed in absolute time (date, hour). 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.

A total number of 8 different ship movements can be distinguished in the existing situation:

no	*ship movement*	*lane*	*up- or downlockage*
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	Atlantic Ocean to Gatun Lake	west lane	Uplockage
6	Gatun Lake to Atlantic Ocean	west lane	Downlockage
7	Atlantic Ocean to Gatun Lake	east lane	Uplockage
8	Gatun Lake to Atlantic Ocean	east lane	Downlockage

Table 5.1 Ship movements in simulation model

A turn around scenario describes the steps during a so-called 'turn around' (change from northbound ship transits in a lane to southbound ship transits or reverse). In a turn around the water levels in the locks are prepared for the change in ship transit direction. A total number of 8 different turn around scenarios are distinguished in the simulation model.

no	*side of canal*	*turn around*	*lane*
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 5.2 Turn arounds in simulation model

Various types of vessels pass the Panama Canal. Table 2.3 presents an over view of vessels that passed the canal in the fiscal year October 2000 – September 2001; they are grouped in vessel type and net tonnage. 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 (see Section 4.2). The slenderness of the ship is also of importance: the wider the ship the more the return current concentrates in the space under the ship, and the more the intrusion of saltier water near the floor of the basin may be effected. Exchange coefficients in the simulation model, which are applied in step II (movement of ship between two adjacent basins), are defined 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 and slenderness on density flows is included.

For use in the simulation model we define the following three ship classes, which may represent the different ship types that pass the canal:

vessel class	*water displacement S*	*beam*	*length*	*draught*	*percentage of number of transits*
0	0	-	-	-	-
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 5.3 Types of vessels in simulation model

A special vessel class '0' is available for lockage operations without a ship. The simulation model assumes that the draught of the ship is not effected by a variation of the water density.

The subsequent steps in ship-movement scenarios and turn-around scenarios are shown in tables in Section 6.3, together with the selected salt exchange coefficients.

5.4 Dimensions of locks, forebays and taibays

The characteristic dimensions of the lock chambers are presented in Table 2.2. 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 simulation).
Floor level corresponds to the deepest 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. The water volume of a lock chamber is equal to the product of lock chamber area and water depth above the floor:

$$V_{lock} = A_{lock} \cdot (h_{lock} - f_{lock}) = l_{lock} \cdot b_{lock} \cdot d_{lock}$$

Next sizes are used in the simulation for all lock chambers:
l_{lock} = nominal length in Table 2.2 (330 m)
b_{lock} = 33.5 m

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

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

A forebay (or tailbay) in Miraflores Lake / Gatun Lake 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 in the full lake, 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 the lake.
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 flows immediately to the lake. The ship moves from lock to lake (or reverse) and causes a flow from forebay to lock and subsequently from lake to forebay. The same holds for the tailbay. The salt concentration is effected by these water movements and is computed in the salt balance.
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.

5.5 Water levels and water releases of Miraflores Lake and Gatun Lake

5.5.1 Water levels and water releases of Gatun Lake

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 +26.7 m (+87.5 ft) is exceeded). The mean water level of Gatun Lake is about +25.9 m (+85.0 ft); the corresponding water volume is 5.17 km^3. The water level variation of Gatun Lake is shown in Figure 2.1 for the period 1992 - 2001.

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 ten-year period are regarded as typical, representative values and are used as input in the simulation model. These average water level values are shown in next Table 5.4 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 5.4 Gatun Lake: representative water levels and corresponding water volume

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 ten-year period are regarded as typical, representative values and are used as input in the simulation model. They are shown in Table 5.5.

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 5.5 Gatun Lake: representative quantities of daily spilled water and water used for hydropower

The total spilled quantity in a year amounts to about 1900 x 10^6 m^3, being 37% of the total mean volume of Gatun Lake. In addition, each transiting ship causes a water loss of about (25.7 / 3) m * 330 m * 33.5 m * 2 = 0.19 x 10^6 m^3, which results in a total loss of about 2500 x 10^6 m^3 in one year with 36 ship transits a day. Thus, the total water loss from Gatun Lake equals 4400 x 10^6 m^3 in an average year, which is about 85% of the mean volume of Gatun Lake.

5.5.2 Water level and water releases of Miraflores Lake

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, ground water flow, cooling water and spillage of water through Miraflores Spillway. At present the water level in Miraflores Lake is maintained at about +16.6 m (+54.4 ft), 0.25 m higher than in the years up to 1965, see Figure 2.2 (this figure shows the mean, minimum and maximum water levels in a year in the period 1915 – 2001).

A constant water level of +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 daily spilled water quantities of Miraflores Lake and the water quantities used for cooling are shown in Table 5.6. 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 5.6 Miraflores Lake: daily spilled / used water quantities in 2001

The values in Table 5.6 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 5.7; these values are regarded as representative values and are used in the simulation model.

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

The daily spilled and used water quantities of Gatun Lake and Miraflores Lake are shown in the graph of Figure 5.6.

5.5.3 Effect of water level changes and water releases

Water levels and corresponding water volumes of the lakes are prescribed for each day of a case in the simulation model. Also the water quantities that are daily spilled or used for other purposes are prescribed. The effect of water level changes on the salt concentration of the lakes is computed at the start of each day; the effects of water releases are evaluated through special scenarios (see also Section 5.8.4).

5.6 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 is PLD +0.30 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 is PLD +0.06 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 is the period and the amplitude that counts, rather than a full reproduction of the course of the tidal movement.
The tidal movement in the tailbay of Miraflores Locks (Figure 5.4) 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 tidal variation: $+2.68 \text{ m} < h_{tailbay} < -2.07 \text{ m}$.

The tidal movement in the tailbay of Gatun Locks (Figure 5.5) 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 tidal variation: $+0.26\ m < h_{tailbay} < -0.14\ m$.
The simulation model starts the computation of tidal movements from the arbitrarily selected date of 1 January 1970 onwards.

The salt concentration in the tailbays at the seaside of the locks fluctuates as a function of the season (see Section 4.1); this holds in particular for the tailbay at the Pacific side. The salt concentration in the tailbay of Miraflores Locks varies between about 28 ppt (wet season) and 34 ppt (dry season); the effect of a lower temperature in the dry 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 tailbay of Gatun Locks varies slightly about a value of 31 ppt. The following salt concentrations are used in the simulation model:

Month	*Salt concentration tailbay Miraflores Locks (ppt)*	*Salt concentration tailbay Gatun Locks (ppt)*
January	31	30
February	34	31
March	37	32
April	37	32
May	35	32
June	33	31
July	31	30
August	28	30
September	28	30
October	28	30
November	28	30
December	28	30

Table 5.8 Salt concentration in tailbay of Miraflores Locks and tailbay of Gatun Locks

5.7 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 and input functions. At the start of a simulation run, however, an initial value must also be given to the water levels in all lock chambers and the salt concentrations in the lock chambers, 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. The mean high water levels in the lock chambers, as shown in Table 6.2, are by default selected as initial values.

5.8 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 in the locking process for a single ship movement and contains also other relevant data which is necessary for the execution of the scenario. Special scenarios are turn-around scenarios and water-release scenarios.
The salt concentrations and water levels of tailbays at the seaside of the locks, as well as water levels and water volumes of the lakes form input for the simulation model. At the start of a case the initial value of the status parameters are prescribed, see Section 5.7.
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. All these water releases form input for the simulation model; they 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 when 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 6.3) are prescribed through the input table 'Coefficient Set'.

Salt concentrations are either volume-averaged values (in basins) or time-averaged values (in water intakes or water outlets). A salt concentration multiplied by a water volume represents a quantity of salt. The salt exchange SE in the salt balance represents the quantity of salt (in kg) that 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.
In next sections we explain also in which way the exchange coefficient e_x can be derived from the salinity measurements. Reference is made to measurement phases a - c in tailbays and forebays, and phases 1 - 5 in lock chambers (see Section 3.2).

5.8.1 Nodal status evaluation 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); 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.

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
- 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

The exchange coefficient e_x in step I is used 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 high basin to lower basin to equalize the water levels. The exchange coefficient e_x is 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 coefficient e_x can be greater than 1; this indicates that the water portion that is transferred from high basin to low basin has a higher salt concentration than the initial water in the high basin (volume averaged). The reason is that the water is drawn from the water body near the floor, which, generally, has a higher than average salt concentration.

In step II the ship moves from low basin to high basin. Simultaneously, a water quantity equal to the volume S of the ship is transferred from high basin to low basin. This return water may contain a certain quantity of salt. The additional salt exchange between the two basins caused by density flows is quantified with the help of the exchange coefficient e_x, the reference volume V_{ref} (equal to the quantity of water in the high basin) and the initial salt-concentration difference between the two basins. This coefficient can either by positive, nill or negative (see also Section 6.3). The exchange coefficient e_x in step II is dependent on the ship volume S. Input for the simulation model is the value of e_x for S = 0. The value of e_x applied in the computation is:

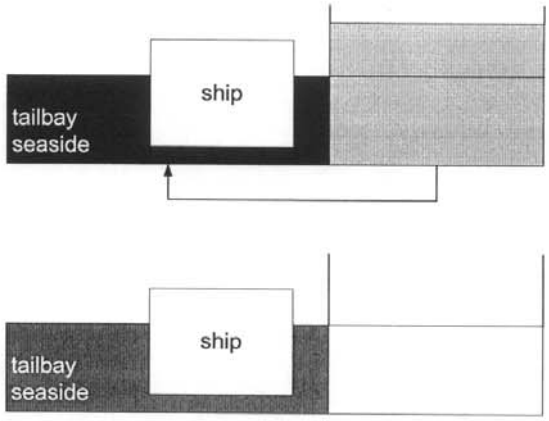
$$e_x = \left(1 - \frac{S}{V_{ref}}\right) \cdot e_{x0}$$

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

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

step I: equalize water level in low basin (with ship) with water level in high basin (without ship); 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}, and $h_{tailbay}$ (= input)

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

salt balance

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

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

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

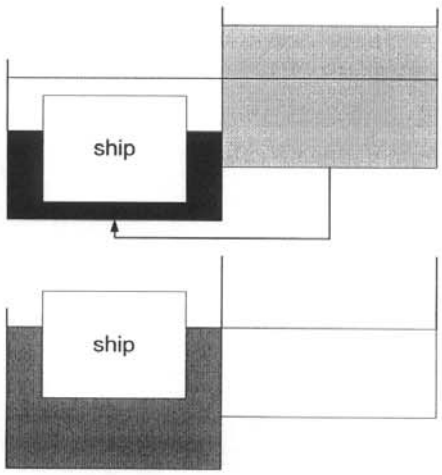
required salinity measurements in high basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at high water c_{high1}
phase 5: volume-averaged salinity of lock chamber at low water c_{high2}

Check:

$$SE = V_{ref} \cdot c_{outlet} = e_x \cdot V_{ref} \cdot c_{high1}$$

required salinity measurements in high basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at high water c_{high1}
required salinity measurements in low basin (tailbay seaside) for derivation of e_x:
phase a: time-averaged salinity of spill water c_{outlet}

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}

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

check: $h_{low2} > maxh_{low}$?
if yes, $h_{low2} = maxh_{low}$
$h_{high2} = h_{low2}$
check: $h_{high2} < minh_{high}$?
if yes, $h_{high2} = minh_{high}$
$h_{low2} = h_{high2}$
$d_{low2} = h_{low2} - f_{low}$

$V_{low2} = (d_{low2} \cdot A_{low}) - S$
$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = d_{high2} \cdot A_{high}$
$V_{ref} = (h_{high1} - h_{high2}) \cdot A_{high}$

salt balance

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

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

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

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at high water c_{high1}
phase 5: volume-averaged salinity of lock chamber at low water c_{high2}

Check:

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

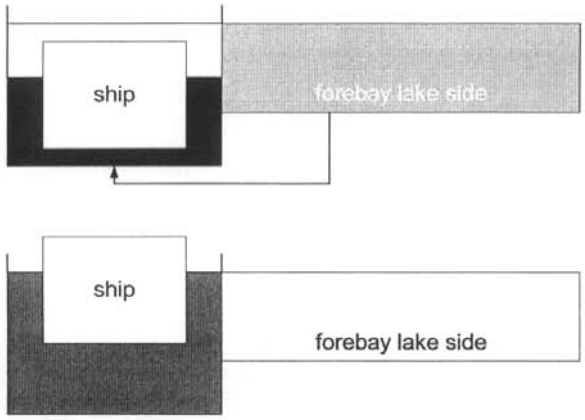
required salinity measurements in high basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at high water c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at low water c_{low1}
phase 3: volume-averaged salinity of lock chamber at high water c_{low2}

Another check would be:

$SE = V_{ref} \cdot c_{culvert} = e_x \cdot V_{ref} \cdot c_{high1}$

in which $c_{culvert}$ is the time-averaged salinity level of the water that is spilled from high lock to low lock; this would require a salinity measurement in the main culvert of the locks, which is not feasible.

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}

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

salt balance

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

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

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

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

$SE = V_{ref} \cdot c_{intake} = e_x \cdot V_{ref} \cdot c_{high1}$

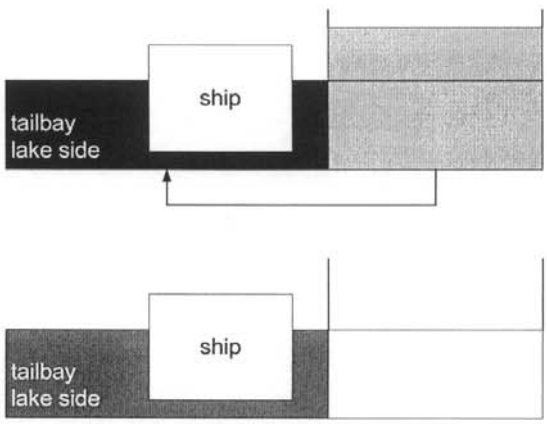
required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase c: volume-averaged salinity of forebay before take off of water c_{high1}
phase a: time-averaged salinity of intake water c_{intake}

Check:

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

required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase c: volume-averaged salinity of forebay before take off of water c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at low water c_{low1}
phase 3: volume-averaged salinity of lock chamber at high water c_{low2}

low basin = tailbay lake side, 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_{lake} (= input), V_{lake} (= input)

$h_{low2} = h_{low1} = h_{lake}$
$h_{high2} = h_{lake}$
check: $h_{high2} < \min h_{high}$?
if yes, $h_{high2} = \min h_{high}$
note: in practice the water level in the lake shall be raised
$d_{low2} = d_{low1} = d_{tailbay} = (h_{lake} - f_{sill})$
$V_{low2} = V_{low1} = V_{tailbay} = d_{low2} \cdot A_{tailbay}$

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

salt balance

Known values at the beginning of step: c_{high1}, c_{low1} (= $c_{tailbay1}$), c_{lake1}

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_x \cdot V_{ref} \cdot c_{high1}) - (V_{ref} \cdot c_{low1})}{V_{low2}} = c_{tailbay2}$$

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

$$c_{lake2} = c_{lake1} + \frac{V_{ref}}{V_{lake}} . c_{tailbay1}$$

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at high water c_{high1}
phase 5: volume-averaged salinity of lock chamber at low water c_{high2}

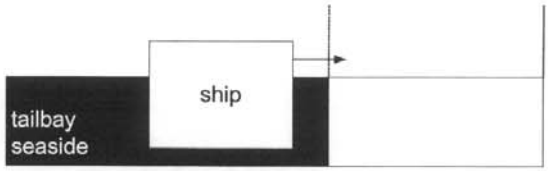
Check:

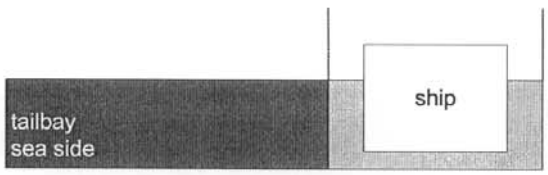
$SE = V_{ref} \cdot c_{outlet} = e_x \cdot V_{ref} \cdot c_{high1}$

required salinity measurements in high basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at high water c_{high1}
required salinity measurements in low basin (tailbay lake side):
phase a: time-averaged salinity of spill water c_{outlet}

step II: 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}, $c_{tailbay}$ (input)

$c_{low1} = c_{tailbay}$

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

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{high1}
phase 2: volume-averaged salinity of lock chamber after entry of ship c_{high2}

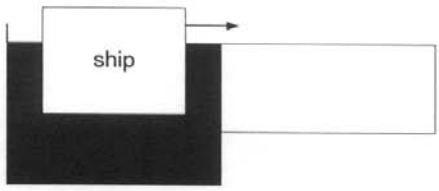
required salinity measurements in low basin (tailbay seaside) for derivation of e_x:
phase b: volume-averaged salinity of tailbay before passage of ship c_{low1}

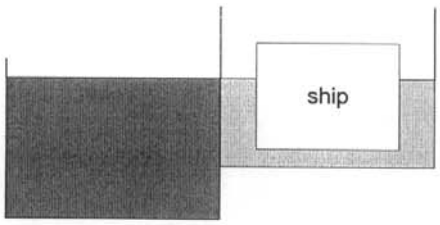
Check:

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{high1}
required salinity measurements in low basin (tailbay seaside) for derivation of e_x:
phase b: volume-averaged salinity of tailbay before passage of ship c_{low1}
phase c: volume-averaged salinity of tailbay after passage of ship c_{low2}

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}

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

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

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

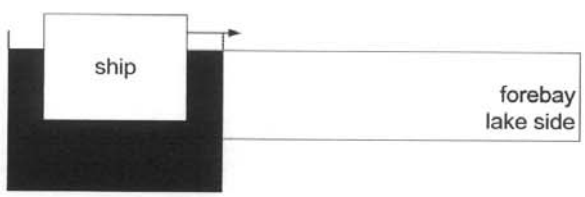
required salinity measurements in high basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{high1}
phase 2: volume-averaged salinity of lock chamber after entry of ship c_{high2}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock chamber before exit of ship c_{low1}

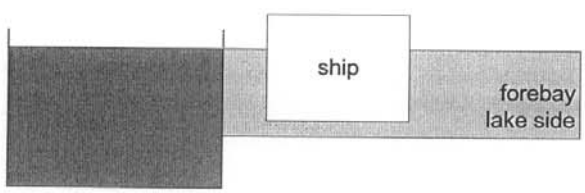
Check:

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock chamber before exit of ship c_{low1}
phase 4: volume-averaged salinity of lock chamber after exit of ship c_{low2}

low basin = lock, high basin = forebay lake side,





water balance

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

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

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

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

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

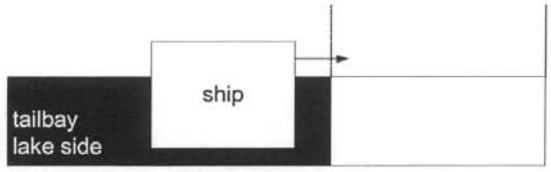
required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase b: volume-averaged salinity of forebay before passage of ship c_{high1}
phase c: volume-averaged salinity of forebay after passage of ship c_{high2}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock chamber before exit of ship c_{low1}

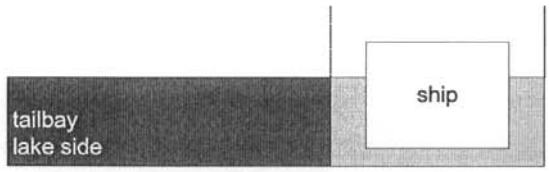
Check:

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

required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase b: volume-averaged salinity of forebay before passage of ship c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock chamber before exit of ship c_{low1}
phase 4: volume-averaged salinity of lock chamber after exit of ship c_{low2}

low basin = tailbay lake side, 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_{lake} (= input)

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

salt balance

Known values at the beginning of step: c_{high1}, c_{low1} (= $c_{tailbay1}$), c_{lake1}

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) - e_x \cdot V_{ref} \cdot (c_{low1} - c_{high1}) + (S \cdot c_{high1}) - (S \cdot c_{low1})}{V_{low2}} = c_{tailbay2}$$

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

$$c_{lake2} = c_{lake1} + \frac{S}{V_{lake}} \cdot c_{tailbay1}$$

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{high1}
phase 2: volume-averaged salinity of lock chamber after entry of ship c_{high2}
required salinity measurements in low basin (tailbay lake side) for derivation of e_x:
phase b: volume-averaged salinity of tailbay before passage of ship c_{low1}

Check:

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{high1}
required salinity measurements in low basin (tailbay lake side) for derivation of e_x:
phase b: volume-averaged salinity of tailbay before passage of ship c_{low1}
phase c: volume-averaged salinity of tailbay after passage of ship c_{low2}

Special step: exchange of salt water between forebay and lake and between lake and tailbay

The forebays and tailbays of the locks are in open connection with the lakes. After an uplocking ship has passed the forebay / tailbay or after a turn around the salt concentration of the forebay / tailbay has changed. Density differences exist between the water in the forebay / tailbay 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}, $c_{forebay1}$

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

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

low basin is lake, high basin = tailbay

salt balance

Known values at the beginning of step: $c_{tailbay1}$, c_{lake1}

$$c_{lake2} = c_{lake1} - e_x.(c_{lake1} - c_{tailbay1}).\frac{V_{tailbay}}{V_{lake}}$$

$$c_{tailbay2} = c_{tailbay1} + e_x.(c_{lake1} - c_{tailbay1})$$

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 / tailbay becomes equal to the salt concentration in the lake).

Assuming that the salt exchange process is a lineair 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 both forebays in Gatun Lake and T = 1800 s for forebay and tailbay in Miraflores Lake, starting from the assumption that salt concentration differences between forebay and lake or lake and tailbay are up to 2 ppt and propagation velocities of a salt tongue are in the order of 0.1 – 0.3 m/s.

5.8.2 Nodal status evaluation 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); 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.

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
- 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

The exchange coefficient e_x in step I is used 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 high basin to lower basin to equalize the water levels. The exchange coefficient e_x is 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 coefficient e_x can be greater than 1; this indicates that the water portion that is transferred from high basin to low basin has a higher salt concentration than the initial water in the high basin (volume averaged). The reason is that the water is drawn from the water body near the floor, which, generally, has a higher than average salt concentration.

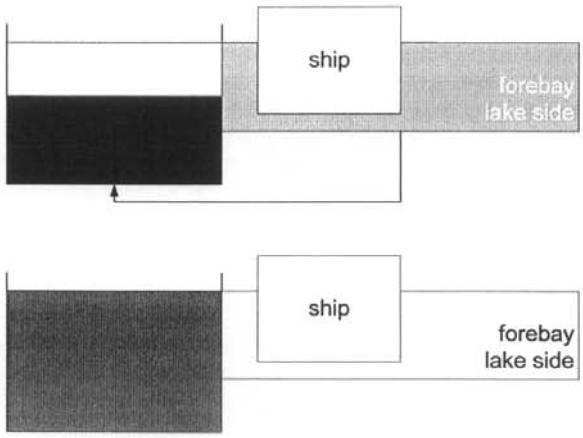
In step II the ship moves from high basin to low basin. Simultaneously, a water quantity equal to the volume S of the ship is transferred from low basin to high basin. This return water may contain a certain quantity of salt. The additional salt exchange between the two basins caused by density flows is quantified with the help of the exchange coefficient e_x, the reference volume V_{ref} (equal to the quantity of water in the high basin) and the initial salt-concentration difference between the two basins. This coefficient can either by positive, nill or negative (see also Section 6.3). The exchange coefficient e_x in step II is dependent on the ship volume S. Input for the simulation model is the value of e_x for S = 0. The value of e_x applied in the computation is:

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

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

step I: equalize water level in low basin (without ship) with water level in high basin (with ship) ; 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}

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

salt balance

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

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

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

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

$$SE = V_{ref} \cdot c_{intake} = e_x \cdot V_{ref} \cdot c_{high1}$$

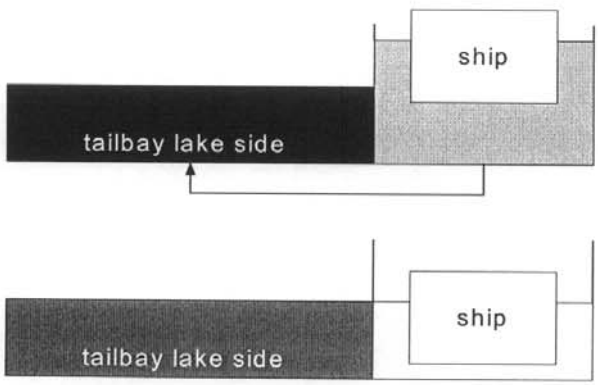
required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase c: volume-averaged salinity of forebay before take off of water c_{high1}
phase a: time-averaged salinity of intake water c_{intake}

Check:

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

required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase c: volume-averaged salinity of forebay before take off of water c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at low water c_{low1}
phase 5: volume-averaged salinity of lock chamber at high water c_{low2}

high basin = lock, low basin = tailbay lake side



water balance

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

h_{high2} = h_{lake}
check: $h_{high2} < minh_{high}$?
if yes, $h_{high2} = minh_{high}$
note: in practice the water level in the lake shall be raised

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

salt balance

Known values at the beginning of step: c_{high1}, c_{low1} (= $c_{tailbay1}$), c_{lake1}

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

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_x \cdot V_{ref} \cdot c_{high1}) - (V_{ref} \cdot c_{low1})}{V_{low2}} = c_{tailbay2}$$

$$c_{lake2} = c_{lake1} + \frac{V_{ref}}{V_{lake}} . c_{tailbay1}$$

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

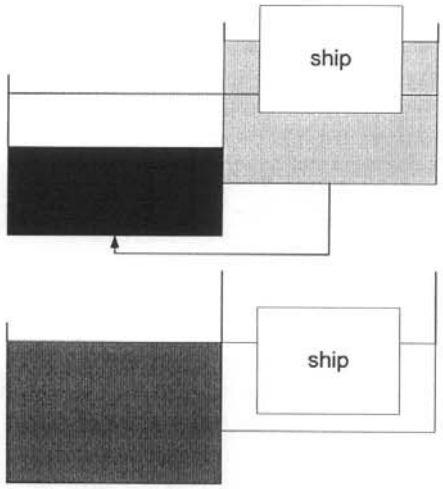
required salinity measurements in high basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at high water c_{high1}
phase 3: volume-averaged salinity of lock chamber at low water c_{high2}

Check:

$SE = V_{ref} \cdot c_{outlet} = e_x \cdot V_{ref} \cdot c_{high1}$

required salinity measurements in high basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at high water c_{high1}
required salinity measurements in low basin (tailbay lake side):
phase a: time-averaged salinity of spill water c_{outlet}

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}

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

check: $h_{high2} < \min h_{high}$?
if yes, $h_{high2} = \min h_{high}$

$h_{low2} = h_{high2}$

check: $h_{low2} > \max h_{low}$?
if yes, $h_{low2} = \max h_{low}$
$h_{high2} = h_{low2}$

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

$V_{high2} = (d_{high2} \cdot A_{high}) - S$

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

$V_{low2} = d_{low2} \cdot A_{low}$

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

salt balance

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

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

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

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at high water c_{high1}
phase 3: volume-averaged salinity of lock chamber at low water c_{high2}

Check:

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

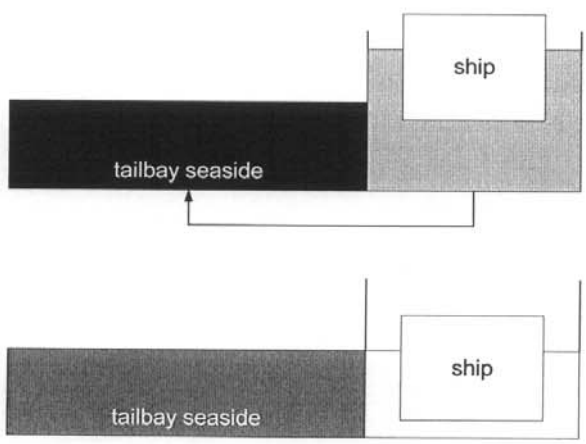
required salinity measurements in high basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at high water c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 4: volume-averaged salinity of lock chamber at low water c_{low1}
phase 5: volume-averaged salinity of lock chamber at high water c_{low2}

Another check would be:

$$SE = V_{ref} \cdot c_{culvert} = e_x \cdot V_{ref} \cdot c_{high1}$$

in which $c_{culvert}$ is the time-averaged salinity level of the water that is spilled from high lock to low lock; this would require a salinity measurement in the main culvert of the locks, which is not feasible.

high basin = lock, low basin = tailbay sea



water balance

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

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

salt balance

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

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

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at high water c_{high1}
phase 3: volume-averaged salinity of lock chamber at low water c_{high2}

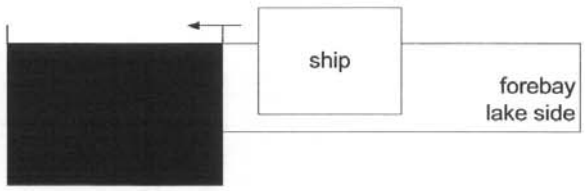
Check:

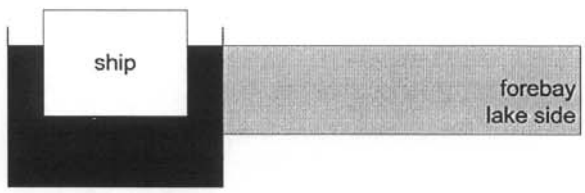
$$SE = V_{ref} \cdot c_{outlet} = e_x \cdot V_{ref} \cdot c_{high1}$$

required salinity measurements in high basin (lock) for derivation of e_x:
phase 2: volume-averaged salinity of lock chamber at high water c_{high1}
required salinity measurements in low basin (tailbay seaside) for derivation of e_x:
phase a: time-averaged salinity of spill water c_{outlet}

step II: 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: V_{lake} (= input), 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}

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

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

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

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

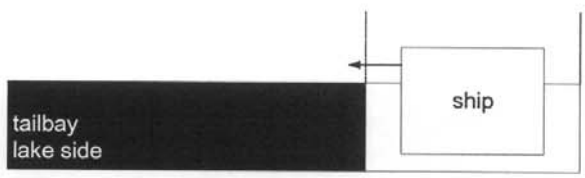
required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase b: volume-averaged salinity of forebay before passage of ship c_{high1}
phase c: volume-averaged salinity of forebay after passage of ship c_{high2}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{low1}

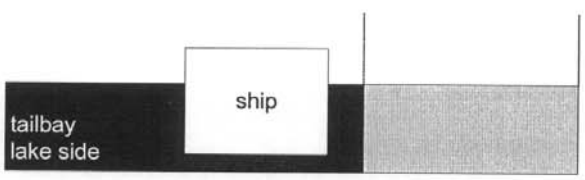
Check:

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

required salinity measurements in high basin (forebay lake side) for derivation of e_x:
phase b: volume-averaged salinity of forebay before passage of ship c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{low1}
phase 2: volume-averaged salinity of lock chamber after entry of ship c_{low2}

high basin = lock, low basin = tailbay lake side





water balance

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

$h_{high2} = h_{high1}$

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

salt balance

Known values at the beginning of step: c_{high1}, c_{low1} (= $c_{tailbay1}$), c_{lake1}

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

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) - e_x \cdot V_{ref} \cdot (c_{low1} - c_{high1}) - (S \cdot c_{low1}) + (S \cdot c_{lake1})}{V_{low2}} = c_{tailbay2}$$

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

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

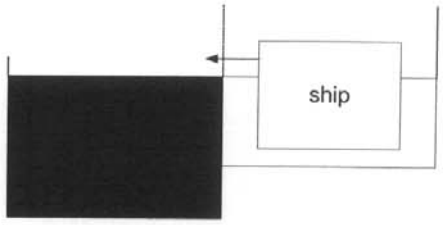
required salinity measurements in high basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock before exit of ship c_{high1}
phase 4: volume-averaged salinity of lock after exit of ship c_{high2}
required salinity measurements in low basin (tailbay lake side) for derivation of e_x:
phase b: volume-averaged salinity of tailbay before passsage of ship c_{low1}

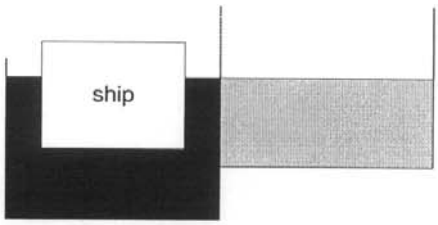
Check:

$$SE = (V_{low1} \cdot c_{low1}) - (V_{low2} \cdot c_{low2}) = (e_x \cdot V_{ref} \cdot (c_{low1} - c_{high1})) + (S \cdot c_{low1}) - (S \cdot c_{lake1})$$

required salinity measurements in high basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock before exit of ship c_{high1}
required salinity measurements in low basin (tailbay lake side) for derivation of e_x:
phase b: volume-averaged salinity of tailbay before passsage of ship c_{low1}
phase c: volume-averaged salinity of tailbay after passage of ship c_{low2}

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}

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

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

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock chamber before exit of ship c_{high1}

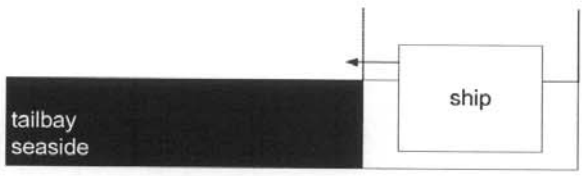
phase 4: volume-averaged salinity of lock chamber after exit of ship c_{high2}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{low1}

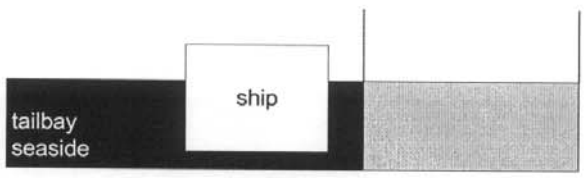
Check:

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock chamber before exit of ship c_{high1}
required salinity measurements in low basin (lock) for derivation of e_x:
phase 5: volume-averaged salinity of lock chamber before entry of ship c_{low1}
phase 2: volume-averaged salinity of lock chamber after entry of ship c_{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}, $c_{tailbay}$ (input)

$c_{low1} = c_{tailbay}$

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

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock before exit of ship c_{high1}
phase 4: volume-averaged salinity of lock after exit of ship c_{high2}
required salinity measurements in low basin (tailbay seaside) for derivation of e_x:
phase b: volume-averaged salinity of forebay before passsage of ship c_{low1}

Check:

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

required salinity measurements in high basin (lock) for derivation of e_x:
phase 3: volume-averaged salinity of lock before exit of ship c_{high1}
required salinity measurements in low basin (tailbay seaside) for derivation of e_x:
phase b: volume-averaged salinity of tailbay before passsage of ship c_{low1}
phase c: volume-averaged salinity of tailbay after passage of ship c_{low2}

Special step: exchange of salt water between forebay and lake and between lake and forebay

The forebays and tailbays of the locks are in open connection with the lakes. After a downlocking ship has passed the forebay / tailbay or after a turn around the salt concentration in the forebay / tailbay has changed. Density differences exist between the water in the forebay / tailbay and the water in the lake, and as a result density-driven exchange flows occur. The quantity of salt that is exchanged between forebay / tailbay 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}, $c_{forebay1}$

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

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

high basin = tailbay, low basin is lake

salt balance

Known values at the beginning of step: $c_{tailbay1}$, c_{lake1}

$$c_{lake2} = c_{lake1} - e_x \cdot (c_{lake1} - c_{tailbay1}) \cdot \frac{V_{tailbay}}{V_{lake}}$$

$$c_{tailbay2} = c_{tailbay1} + e_x \cdot (c_{lake1} - c_{tailbay1})$$

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 / tailbay becomes equal to the salt concentration in the lake).

Assuming that the salt exchange process is a lineair function of time the following relationship is applied in the simulation:

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

with

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

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

A period T = 3600 s is selected for both forebays in Gatun Lake and T = 1800 s for forebay and tailbay in Miraflores Lake, starting from the assumption that salt concentration differences between forebay and lake or lake and tailbay are up to 2 ppt and propagation velocities of a salt tongue are in the order of 0.1 – 0.3 m/s.

5.8.3 Turn arounds

The activities executed during turn arounds and the effect of these activities on salt concentrations in the various basins are described in this section.

Turn around Pacific side; from northbound to southbound transits

Note: Equations are presented for west lane; for east lane: replace W by E in equations.

After the last northbound vessel has passed the locks at the Pacific side (uplockage), the locks have to be prepared for the first southbound ship (downlockage). Water levels in locks A-west, B-west, and C-west are high. Only the water level in Lock A-west has to be lowered to facilitate discharge of water from Lock B-west to Lock A-west during lockage of the first southbound ship. The water of Lock A-west is discharged into the Pacific Entrance.

Single step
The water level in Lock A-west is lowered and equalized with the water level of the seaside tailbay.

water balance

Known values at the beginning of step: hAW_1, dAW_1, VAW_1 and hPO (= $h_{tailbay}$ = input)

hAW_2 = hPO = $h_{tailbay\ sea}$
check: hAW_2 > maxhAW ?
if yes, hAW_2 = maxhAW
hAW < minhAW ?
if yes, hAW_2 = minhAW
note: in practice lock operations will be delayed until the tide has sufficiently changed
dAW_2 = hAW_2 - fAW
VAW_2 = dAW_2 . AAW
V_{ref} = (hAW_1 – hAW_2) . AAW

salt balance

Known value at the beginning of step: cAW_1

$$cAW_2 = \frac{(VAW_1 \cdot cAW_1) - (e_x \cdot V_{ref} \cdot cAW_1)}{VAW_2}$$

Turn around Pacific side; from southbound to northbound transits

Note: Equations are presented for west lane; for east lane: replace W by E in equations.

After the last southbound vessel has passed the locks at the Pacific side (downlockage), the locks have to be prepared for the first northbound ship (uplockage). Water levels in locks A-west, B-west, and C-west are low. Only the water level in Lock B-west has to be raised to facilitate discharge of water from Lock B-west to Lock A-west during lockage of the first northbound ship. Lock B-west is filled with water from Miraflores Lake.

Single step
The water level in Lock B-west is raised and equalized with the water level of Miraflores Lake.

Water balance

Known values at the beginning of step: hML (= h_{lake} = input), $h_{forebay1}$, $d_{forebay1}$, $V_{forebay1}$, hBW_1, dBW_1, VBW_1

hBW_2 = hML = h_{lake}
check: hBW_2 > maxhBW ?
if yes, hBW_2 = maxhBW
note: in practice the water level of Miraflores Lake shall be lowered
dBW_2 = hBW_2 - fBW
VBW_2 = dBW_2 . ABW
$h_{forebay2}$ = $h_{forebay1}$ = hML
$d_{forebay2}$ = $d_{forebay1}$ = hML - f_{sill}
$V_{forebay2}$ = $V_{forebay1}$ = $d_{forebay1}$. $A_{forebay}$
V_{ref} = (hBW_2 – hBW_1) . ABW

salt balance

Known values at the beginning of step: $c_{forebay1}$, cBW_1

$$cBW_2 = \frac{(VBW_1 \cdot cBW_1) + (e_x \cdot V_{ref} \cdot c_{forebay1})}{VBW_2}$$

$$c_{forebay2} = \frac{(V_{forebay1} \cdot c_{forebay1}) - (e_x \cdot V_{ref} \cdot c_{forebay1})}{V_{forebay2}}$$

Note: this step is followed by the special step described at the end of Section 5.8.1.

Turn around Atlantic side; from southbound to northbound transits

Note: Equations are presented for west lane; for east lane: replace W by E in equations.

After the last southbound vessel has passed the locks at the Atlantic side (uplockage), the locks have to be prepared for the first northbound ship (downlockage). Water levels in locks D-west, E-west, and F-west are high. Water levels in Lock D-west and Lock E-west have to be lowered to facilitate discharge of water from Lock F-west to Lock E-west and subsequently from Lock E-west to Lock D-west during lockage of the first southbound ship. Three steps are necessary: (i) discharge water from Lock D-west into the Atlantic Entrance, (ii) discharge water from Lock E-west into Lock D-west, and (iii) discharge water from Lock D-west into the Atlantic Entrance.

Step 1
The water level in Lock D-west is lowered and equalized with the water level of the seaside tailbay (water is discharged from Lock D-west into the Atlantic Entrance).

water balance

Known values at the beginning of step: hDW_1, dDW_1, VDW_1 and hAO (= $h_{tailbay}$ = input)

hDW_2 = hAO = $h_{tailbay}$
check: hDW_2 > maxhDW ?
if yes, hDW_2 = maxhDW
hDW < minhDW ?
if yes, hDW_2 = minhDW
note: in practice exceedance of maximum or minimum water level will not occur since the tidal variation is only small
dDW_2 = hDW_2 - fDW
VDW_2 = dDW_2 . ADW
V_{ref} = (hDW_1 – hDW_2) . ADW

salt balance

Known value at the beginning of step: cDW_1

$$cDW_2 = \frac{(VDW_1 \,.\, cDW_1) - (e_x \,.\, V_{ref} \,.\, cDW_1)}{VDW_2}$$

step 2
The water level of Lock E-west is lowered and equalized with the water level in Lock D-west (water is discharged from Lock E-west into Lock D-west).

water balance

Known values at the beginning of step: hEW_1, dEW_1, VEW_1, hDW_1, dDW_1, VDW_1

$$hDW_2 = hDW_1 + \frac{AEW \,.\, (hEW_1 - hDW_1)}{AEW + ADW}$$

check: $hDW_2 > maxhDW$?
if yes, the surplus water quantity is discharged into Atlantic Entrance,
$hDW_2 = maxhDW$,

$hEW_2 = hDW_2$

check: $hEW_2 < minhEW$?
if yes, an additional water quantity is supplied from Gatun Lake,
$hEW_2 = minhEW$,
$hDW_2 = hEW_2$,

$dDW_2 = hDW_2 - fDW$
$VDW_2 = (dDW_2 \,.\, ADW)$
$dEW_2 = hEW_2 - fEW$
$VEW_2 = dEW_2 \,.\, AEW$
$V_{ref} = (hEW_1 - hEW_2) \,.\, AEW$

salt balance

Known value at the beginning of step: cEW_1 and cDW_1

$$cDW_2 = \frac{(VDW_1 \,.\, cDW_1) + (e_x \,.\, V_{ref} \,.\, cEW_1)}{VDW_2}$$

$$cEW_2 = \frac{(VEW_1 \,.\, cEW_1) - (e_x \,.\, V_{ref} \,.\, cEW_1)}{VEW_2}$$

Step 3
The water level in Lock D-west is lowered again and equalized with the water level of the seaside tailbay (water is discharged from Lock D-west into the Atlantic Entrance).

water balance

Known values at the beginning of step: hDW_1, dDW_1, VDW_1 and hAO (= $h_{tailbay}$ = input)

$hDW_2 = hAO = h_{tailbay}$
check: $hDW_2 > maxhDW$?
if yes, $hDW_2 = maxhDW$
$hDW < minhDW$?
if yes, $hDW_2 = minhDW$
note: in practice exceedance of maximum or minimum water level will not occur since the tidal variation is only small

$dDW_2 = hDW_2 - fDW$
$VDW_2 = dDW_2 \,.\, ADW$
$V_{ref} = (hDW_1 - hDW_2) \,.\, ADW$

salt balance

Known value at the beginning of step: cDW_1

$$cDW_2 = \frac{(VDW_1 \cdot cDW_1) - (e_x \cdot V_{ref} \cdot cDW_1)}{VDW_2}$$

Turn around Atlantic side; from northbound to southbound transits

Note: Equations are presented for west lane; for east lane: replace W by E in equations.

After the last northbound vessel has passed the locks at the Atlantic side (downlockage), the locks have to be prepared for the first southbound ship (uplockage). Water levels in locks D-west, E-west, and F-west are low. Water levels in Lock E-west and Lock F-west have to be raised to facilitate discharge of water from Lock E-west to Lock D-west and subsequently from Lock F-west to Lock E-west during lockage of the first southbound ship. Three steps are necessary: (i) fill Lock F-west, (ii) discharge water from Lock F-west into Lock E-west, and (iii) fill Lock F-west.

Step 1
The water level in Lock F-west is raised and equalized with the water level of Gatun Lake (water is discharged from Gatun Lake into Lock F-west).

water balance

Known values at the beginning of step: hGL (= input), $h_{forebay1}$, $d_{forebay1}$, $V_{forebay1}$, hFW_1, dFW_1, VFW_1

$hFW_2 = hGL$
check: $hFW_2 > maxhFW$?
if yes, $hFW_2 = maxhFW$
note: in practice the water level of Gatun Lake shall be lowered
$dFW_2 = hFW_2 - fFW$
$VFW_2 = dFW_2 \cdot AFW$
$h_{forebay2} = h_{forebay1} = hGL$
$d_{forebay2} = d_{forebay1} = hGL - f_{sill}$
$V_{forebay2} = V_{forebay1} = d_{forebay1} \cdot A_{forebay}$
$V_{ref} = (hFW_2 - hFW_1) \cdot AFW$

salt balance

Known values at the beginning of step: $c_{forebay1}$, cFW_1

$$cFW_2 = \frac{(VFW_1 \cdot cFW_1) + (e_x \cdot V_{ref} \cdot c_{forebay1})}{VFW_2}$$

$$c_{forebay2} = \frac{(V_{forebay1} \cdot c_{forebay1}) - (e_x \cdot V_{ref} \cdot c_{forebay1})}{V_{forebay2}}$$

Note: this step is followed by the special step described at the end of Section 5.8.2.

Step 2
The water level in Lock E-west is raised and equalized with the water level in Lock F-west (water is discharged from Lock F-west into Lock E-west).

water balance

Known values at the beginning of step: hFW_1, dFW_1, VFW_1, hEW_1, dEW_1, VEW_1

$$hFW_2 = hFW_1 - \frac{AEW \cdot (hFW_1 - hEW_1)}{AEW + AFW}$$

check: $hFW_2 < minhFW$?
if yes, an additional water quantity is supplied from Gatun Lake,
$hFW_2 = minhFW$,
$hEW_2 = hFW_2$
check: $hEW_2 > maxhEW$?
if yes, the surplus water quantity is discharged into Atlantic Entrance,
$hEW_2 = maxhEW$,
$hFW_2 = hEW_2$
$dFW_2 = hFW_2 - fFW$
$VFW_2 = (dFW_2 \cdot AFW)$
$dEW_2 = hEW_2 - fEW$
$VEW_2 = dEW_2 \cdot AEW$
$V_{ref} = (hFW_1 - hFW_2) \cdot AFW$

salt balance

Known value at the beginning of step: cFW_1 and cEW_1

$$cFW_2 = \frac{(VFW_1 \cdot cFW_1) - (e_x \cdot V_{ref} \cdot cFW_1)}{VFW_2}$$

$$cEW_2 = \frac{(VEW_1 \cdot cEW_1) + (e_x \cdot V_{ref} \cdot cFW_1)}{VEW_2}$$

Step 3
The water level in Lock F-west is raised again and equalized with the water level of Gatun Lake (water is discharged from Gatun Lake into Lock F-west).

water balance

Known values at the beginning of step: hGL (= input), $h_{forebay1}$, $d_{forebay1}$, $V_{forebay1}$, hFW_1, dFW_1, VFW_1

$hFW_2 = hGL$
check: $hFW_2 > maxhFW$?
if yes, $hFW_2 = maxhFW$
note: in practice the water level of Gatun Lake shall be lowered
$dFW_2 = hFW_2 - fFW$
$VFW_2 = dFW_2 \cdot AFW$
$h_{forebay2} = h_{forebay1} = hGL$
$d_{forebay2} = d_{forebay1} = hGL - f_{sill}$

$$V_{forebay2} = V_{forebay1} = d_{forebay1} \cdot A_{forebay}$$
$$V_{ref} = (hFW_2 - hFW_1) \cdot AFW$$

salt balance

Known values at the beginning of step: $c_{forebay1}$, cFW_1

$$cFW_2 = \frac{(VFW_1 \cdot cFW_1) + (e_x \cdot V_{ref} \cdot c_{forebay1})}{VFW_2}$$

$$c_{forebay2} = \frac{(V_{forebay1} \cdot c_{forebay1}) - (e_x \cdot V_{ref} \cdot c_{forebay1})}{V_{forebay2}}$$

Note: this step is followed by the special step described at the end of Section 5.8.2.

5.8.4 Lakes: effect of water level changes and releases of water

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

Gatun Lake:

Step 1: evaluate the effect of water level changes on salt concentration

water balance

Known values at the beginning of step: hGL_1 (= h_{lake}) and VGL_1

hGL_2 = read new value from input table
VGL_2 = read new value from input table

salt balance

Known value at the beginning of step: cGL_1

$$cGL_2 = \frac{cGL_1 \cdot VGL_1}{VGL_2}$$

Step 2: evaluate the effect of water releases on salt concentration

water balance

Known values at the beginning of step: hGL_1 and VGL_1

$hGL_2 = hGL_1$
$VGL_2 = VGL_1$

salt balance

Known value at the beginning of step: cGL_1

$$cGL_2 = \frac{(VGL_1 \,.\, cGL_1) - (e_{x1} \,.\, QGL \,.\, cGL_1) - (e_{x2} \,.\, PGL \,.\, cGL_1)}{VGL_2}$$

e_{x1}, e_{x2}: exchange coefficients; no outflow of salt water when $e_{x1} = e_{x2} = 0$

Miraflores Lake:

Step 1: evaluate the effect of water level changes on salt concentration

water balance

Known values at the beginning of step: hML_1 (= h_{lake}) and VML_1

hML_2 = read new value from input table
VML_2 = read new value from input table

salt balance

Known value at the beginning of step: cML_1

$$cML_2 = \frac{cML_1 \,.\, VML_1}{VML_2}$$

Step 2: evaluate the effect of water releases on salt concentration

water balance

Known values at the beginning of step: hML_1 and VML_1

$hML_2 = hML_1$
$VML_2 = VML_1$

salt balance

Known value at the beginning of step: cML_1

$$cML_2 = \frac{(VML_1 \,.\, cML_1) - (e_{x3} \,.\, QML \,.\, cML_1) - (e_{x4} \,.\, PML \,.\, cML_1)}{VML_2}$$

e_{x3}, e_{x4}: exchange coefficients; no outflow of salt water when $e_{x3} = e_{x4} = 0$

5.9 Design of the numerical model

In this section the starting points for the design of the numerical model, that simulates the salt intrusion processes through the locks on the Panama Canal, are presented.
The numerical model allows end users to perform a long term simulation of salt water intrusion. The way the water basins are connected to each other is given and can not be edited by the end user. The end user is able to modify various parameters in order to perform a new simulation.

5.9.1 Requirements

Language and platform

- The system will be built in Java
- The system will run on a Windows 2000 system.
- Data, either edited or computed, are stored in files. A directory structure will be used to manage cases.

Preparing a computation

The end user is able to compose the simulation of the locking process in the following way:

- On detail level relevant parameters of a ship movement can be modified, e.g. the size of a ship. Subsequent steps of a ship movement are queued as a scenario. Each scenario has a starting time and a duration.
- On scenario level a number of scenarios are queued into a day pattern. In a day pattern each scenario has a specified starting time.
- Water levels, water volumes and salt concentrations are stored in an environment as a function of time (date, hour).
- A case consists of a number of day patterns combined with an environment. A case has a start and end date.

Default values of the dimensions of locks and water basins are available in a list. No GIS interface will be used. Locks or basins are selected in order to modify their relevant parameters or to view the calculated results in a table or chart.

Computing the salt water intrusion

The calculation of salt concentrations is based on the exchange of saline water volumes. Apart from the salt water that is displaced by the movement of the ship, the salt water that is exchanged as a result of density flows and filling / emptying of lock chambers is derived through exchange coefficients, which are given in data tables. These coefficients depend on the ship size, ship movement, etc. and include the effects of a non-homogeneous salt concentration (in reality gradients occur in vertical and longitudinal direction of the lock chambers, in the simulation model salt concentrations are volume averaged values).

Results of computations

The computed results are visible for the end user in the following ways:

- Salt concentrations or other variables of basins and locks can be displayed as a function of time.
- The results can be displayed in a chart; results of one or more basins can be displayed at the same time. A graph can be saved as .jpg file. The end user is able to print a graph.
- The results can be displayed in a table. A table can be saved as an Excel spreadsheet. The end user is able to print a table.

Additional requirements

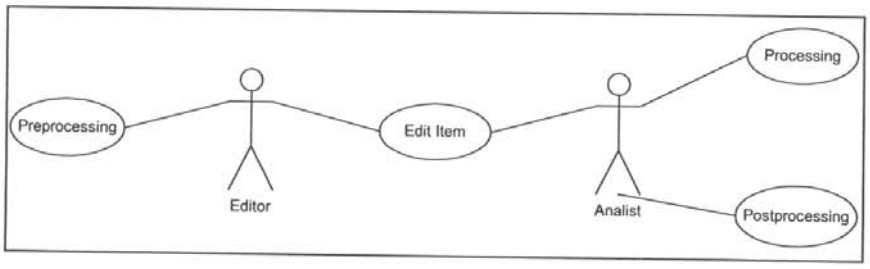
Additional requirements are:

- The system will be delivered including set-up on CD.
- End user documentation in English will be provided

5.9.2 Design of the numerical model

Overview

From the software architecture point of view, running the system consists of four activities. These activities are given in the following use case diagram:



The items contain the following functionality.

Use Case	*Description*
Edit Item	Some basic actions, wich are appropriate for all kind of items.
PreProcessing	The preparation of all data into a case before calculation of the salt water intrusion.
Processing	Using the data of a case, the system computes the salt water intrusion.
PostProcessing	The computed results are viewed in tables and diagrams

The main focus of the first activities lies on the editing of data. Therefore, the role associated to these activities is the role of an editor. The role associated to the last two steps is focused to computing and analysing data. This role is called analist. However, a user always

logs in to the system with the same rights. A user sometimes behaves as an editor and sometimes as an analist, both in the same session. Only to make clear what the different activities contain, the use of different roles is introduced.

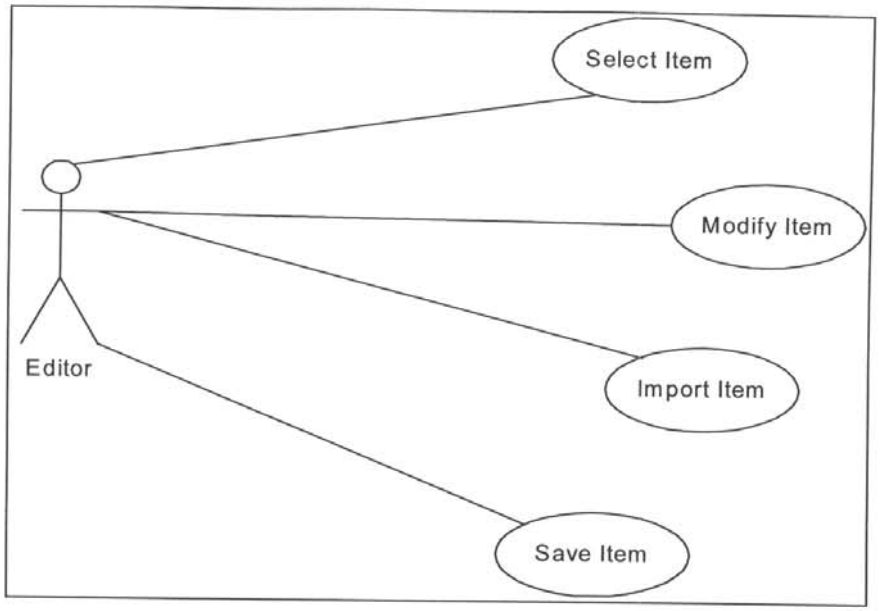
Edit Item

This section describes some basic actions, which can be performed on an item. An item is any set of data in this model. The following items are known:

Item	*Description*	*Editable*
Node	A node contains the properties of a water basin (e.g. volume, water level, salt concentration). The type of node is given. We distinguish the following types: tailbay sea, lock, forebay lake, lake, tailbay lake (in the future situation also water saving basin). For a 'tailbay sea' next time dependent properties are given: salt concentration and water level; for a lake: water level and water volume.	Yes
Gate	A gate forms a connection between two nodes. This can be a real lock gate or the implicit transition of a forebay to a lake, etc.	No
Ship Movement	This is the route a ship follows on a part of it's journey through the Panama Canal. e.g. the route from Pacific Ocean to Gatun Lake through the west locks.	No
Ship	Properties of a ship, i.e. water displacement. Ship types are given in a table.	No
Scenario	A scenario is a sequence of operational steps which are necessary for a ship movement, a 'turn around' or water releases.	Yes
Day Pattern	A day pattern is a sequence of scenarios. Each scenario in this list has a starting time on a day (e.g. 09:00AM). At the start of a day the effects of spillages and hydropower / cooling water use are evaluated.	Yes
Schematisation	The environment contains the water levels of the sea tailbays and lakes as a function of absolute time (e.g. 09:00AM 01/01/2002). Also the salinity of the sea tailbays is included. This data is given in a table or a function.	Yes
Case	A case combines an environment with a day pattern. A start date and end date is given too.	Yes

For each type of item, there is an implementing class with the same name. In the following sections, these classes will be indicated as <Item>.

The tasks to be performed are given in the following use case diagram.

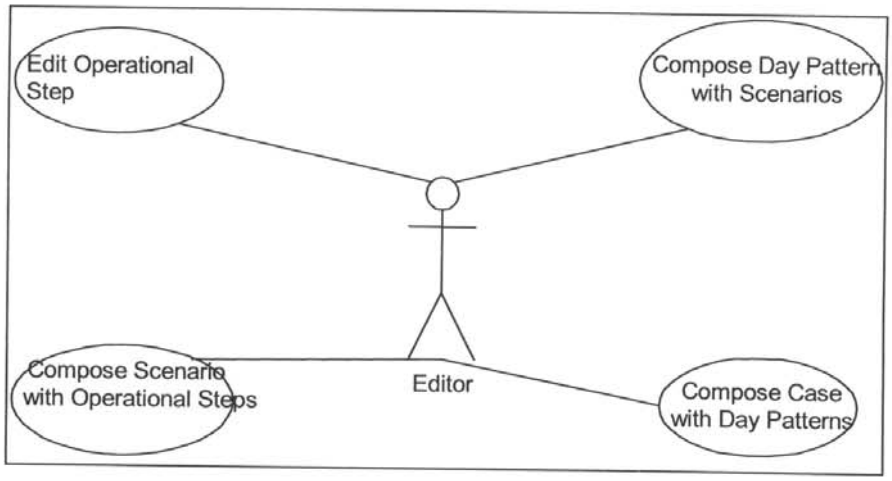


An editor performs the following actions to edit items:

Use Case	*Description*	*Implementing Class*
Select Item	The editor selects an item from a tree. Using this tree, he is also able to create a new item or delete an item. Depending on the node in the tree, the editor knows what kind of item he is dealing with or what kind of item should be created.	ShellTree
Modify Item	To modify an item, it is opened in an edit frame. Each item has it's won, specific edit frame. This allows to edit it's specific item properties, e.g. the start and end date of a case.	<Item> <Item>Editor <Item>Editor r
Import Item	Sometimes it is necessary to refer to another subitem. Then that sub item is imported into the main item (e.g. a salt exchange coefficient set is imported into a case); consequently the main item may contain a number of sub items. The import of a sub item leads to a copy of the sub item into the main item. This is done to prevent unmeant changes of a main item, when a sub item is changed.	<Item> <Item>Editor
Save Item	At last an editor or analist saves the item to file. All data applicable for the item will be saved, being the item itself, any imported sub items and calculated results	<Item>

PreProcessing

The goal of preprocessing is to create the necessary data to perform a useful calculation. Such a set of data is contained by a case. To support the editor, the building of a case is subdivided into four activities, given in the following use case diagram.



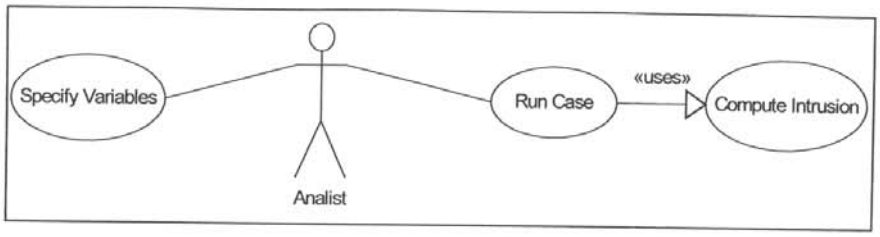
An editor performs the following activities to edit a case:

Use Case	*Description*
Edit Operational Steps	The editor selects a ship movement. Then he specifies the parameters specific for each gate passed in the ship movement
Compose Scenario	To compose a scenario, an editor imports a number of data into the scenario.
Compose Day Pattern with Scenarios	To compose a day pattern, an editor imports a number of scenarios and orders them by assigning start times. An imported scenario is copied into the day pattern.
Compose Case with Day Pattern and Environment	To create a case, an editor imports an environment and a day pattern. He selects a start and end time

All actions described above are implemented with classes described in "Edit Item".

Processing

To compute the salt water intrusion, a user runs the case, also called processing. He takes the following actions:

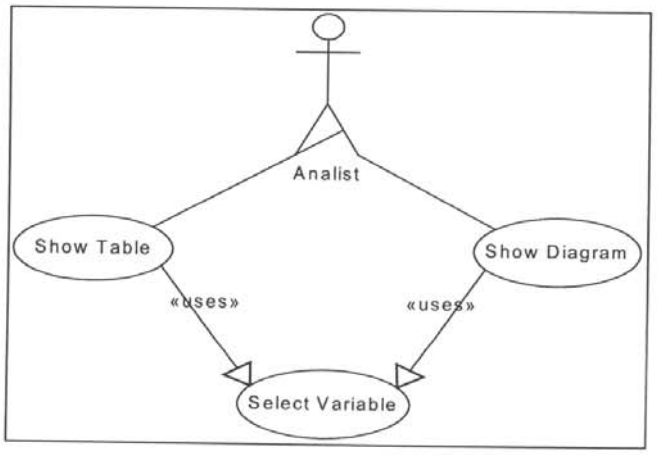


The actions to be taken are the following:

Use Case	*Description*	*Implementing Class*
Specify Variables	This is a possible future extension. Although the data is edited during preprocessing, the analist might wish to vary some parameters over a few values. Then he specifies these variables and fills in a little table, which contains all desired values of the variable.	Case Variable CaseEditor
Run Case	To compute the salt water intrusion, we run the case. Data is produced concerning the salt water concentration and other nodal parameters as a function of time and node. If variables are specified, subruns are created for each value of a variable. For example, if variable A contains n values and variable B contains m values, in total $n \times m$ subruns are performed.	Case SwinRun
Compute Salt Water Intrusion	This will compute the salt water intrusion with a fixed set of input values. Actually, this is a subrun.	SwinRun DataBlock

PostProcessing

For analysing purposes, an analist will view the computed data and compare them to each other. He takes the following actions:



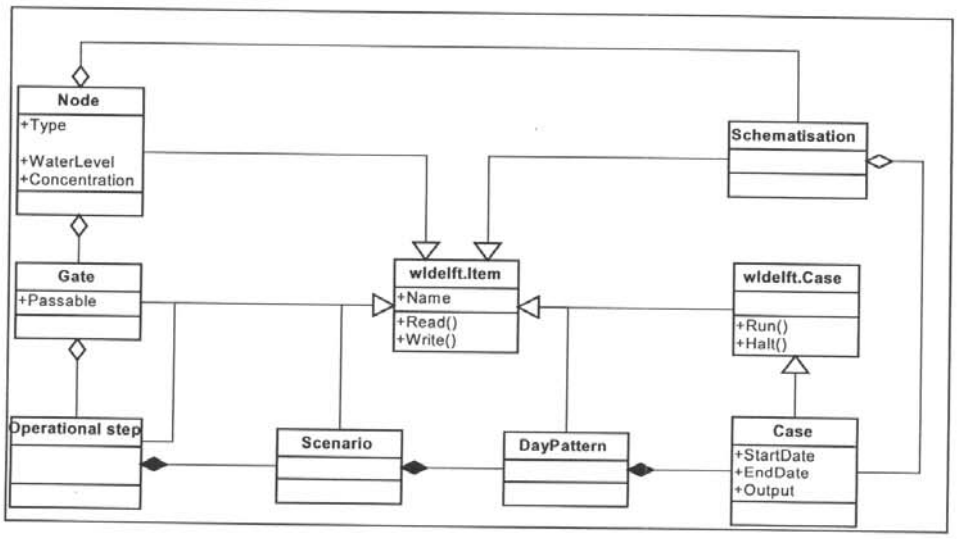
The actions to be taken are the following:

Use Case	*Description*	*Implementing Class*
Show Table	The analist is able to let the system display a table of results. A table consists of several rows and columns, where each cell is filled with the salt concentration or another quantity. Each row represents a day . Each column represents a node (e.g. lock, lake) or day, which can contain more than one value.	DataBlock DataBlockTable
Show Diagram	A diagram of computed data can be displayed. Along the vertical axis, the salt concentration or an other parameter is displayed. Along the horizontal axis the time is displayed.	DataBlock DataBlockChart
Select Variable	When an analist wants to display a table or a diagram, he should select which variables are displayed in which row / column. A common method to indicate these parameters is provided by this use case.	Case DataBlockSelector

5.9.3 Classes

Item classes

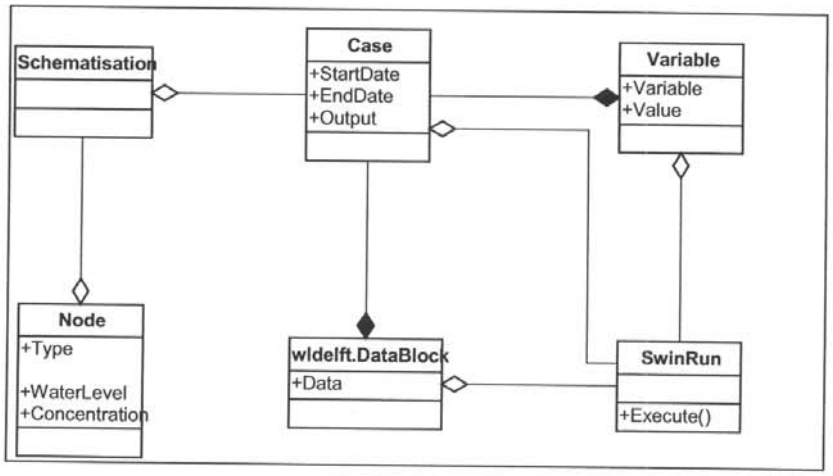
This section describes the classes which represent input data. All classes are derived from the basic class Item.
You can see how classes are composed of other classes. However, it is not displayed that these compositions themselves contain extra data, being the sequence indicator of the sub item in the main item.



Class	*Description*	*Relations*
wldelft.Item	superclass for all data containing classes	
wldelft.Case	superclass for all cases, i.e. classes on which a useful calculation can be performed	
Node	see Edit Item	
Gate	see Edit Item	Points to two nodes, on both sides of the gate
Operational Step	see Edit Item	Refers to a gate, for which this operational step is applicable
Scenario	see Edit Item	Contains a number of operational steps.
DayPattern	see Edit Item	Contains a number of scenarios. The relation itself contains the time of the scenario (e.g. 09:00AM).
Case	see Edit Item	Contains a day pattern and refers to an environment.
Schematisation	see Edit Item	

Calculation classes

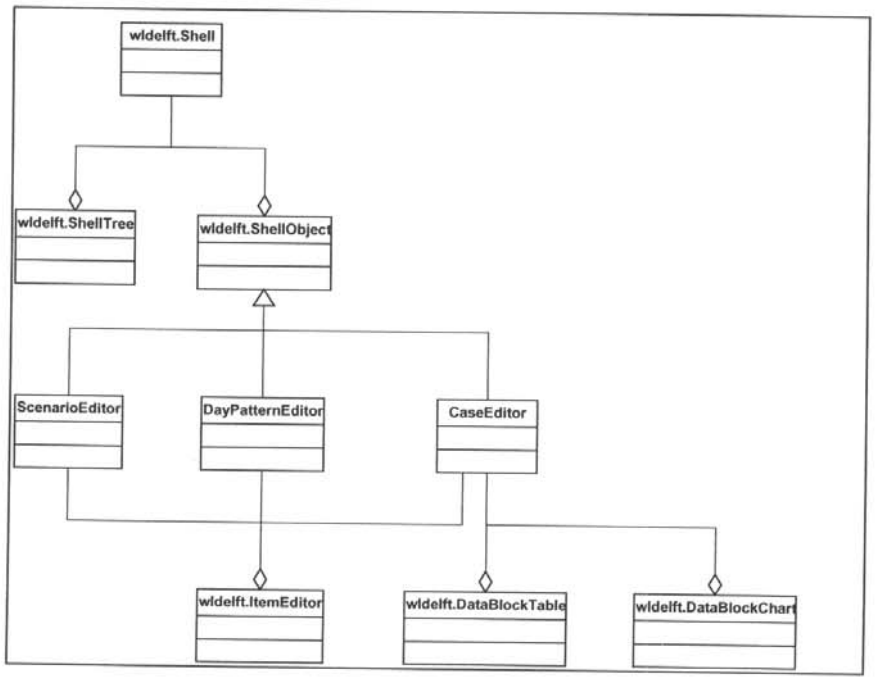
The calculation classes contain calculated data. Their relations with cases are given too.



Class	*Description*	*Relations*
Case	See: Edit Item	Contains a datablock with computed values.
Variable	See: Processing	Refers to a parameter of a node, e.g. the volume
SwinRun	See: Processing	Takes care for the actual calculation. The calculation is performed in background. The case object is used as input.
DataBlock	A 3-dimensional block of data. The axes represent the parameter (salinity or other), the location (node) and the time.	The calculated values are stored in an array. The case defines how often a record is written in theis array, e.g. once per day.
Schematisation	See: Edit Item	Contains a set of node values. These are the values indicating the water level and salinity of the seas.

User Interface classes

The user interfaces is built in several classes.



Class	*Description*	*Relations*
wldelft.Shell	Shows the application, which is configurable for the menu etc.	
wldelft.ShellTree	Shows a tree of items. This tree will be used to select the items to open in an editor, import, show in a diagram or table and delete.	
wldelft.ShellObject	Superclass of all editors. An editor allows the user to edit data of an item	
ScenarioEditor	See: Edit Item	Contains an ItemEditor, in which gate operations can be listed
DayPatternEditor	See: Edit Item	Contains an ItemEditor, in which scenarios can be listed
CaseEditor	See: Edit Item	Contains viewers to display the calculated results
DataBlockTable	See: PostProcessing	Displays the data contained by a DataBlock
DataBlockChart	See: PostProcessing	Displays the data contained by a DataBlock.
wldelft.ItemEditor	General class, in which items can be edited	

6 Testing and validation of the simulation model

Testing and validation of the numerical model that simulates the salt water intrusion process through the locks on the Panama Canal, is the subject of this chapter. The proper functioning of the model is checked and the model is validated with data of wet-season and dry-season salinity measurements (November- December 2001, April 2002).

6.1 Data used for testing and validation

The next input data is used for testing / validation of the simulation model:

- Dimensions of locks: values presented in Table 2.2 are used (nominal length, width and floor level of lock chambers; sill levels of locks for computation of forebay and tailbay volumes). Coping level is selected as the maximum water level in the lock chamber; sill level plus10 m as the minimum water level in the lock chamber.
- Water levels and salt concentrations in seaside forebays: tidal movements are predicted with the formulas presented in Section 5.6; salt concentrations as shown in Table 5.8 are selected for the seaside tailbays.
- Water levels and water volumes of Gatun Lake and Miraflores Lake: monthly values presented in Table 5.4 are selected for Gatun Lake; a constant water level of +16.58 m (+54.4 ft) and a corresponding water volume of 23.80 x 10^6 m^3 (840.65 x 10^6 ft^3) is used for Miraflores Lake.
- Lockages: the ship types and frequencies of ship transits as presented in Table 5.3 are used.
- Spillages and water used for hydropower generation / cooling: the daily water quantities as presented in Table 5.5 (Gatun Lake) and Table 5.7 (Miraflores Lake) are selected.

In test cases also other input data has been used.

6.2 Set up of scenarios, day patterns and cases

For validation of the simulation model we have defined a standard day pattern, that contains the same scenarios and the same sequence of scenarios each day. For the sake of simplicity we have assumed a constant number of 36 ship transits a day (18 transits from Pacific Ocean to Atlantic Ocean, 18 transits from Atlantic Ocean to Pacific Ocean). Consequently, each day pattern contains 72 ship movement scenarios and 16 turn around scenarios (see also Chapter 5). Each day pattern starts with three water-release scenarios (Gatun Spillway, Gatun Hydropower Station, Miraflores Spillway (including cooling water)). The quantities of spilled water and water used for hydropower generation / cooling differ from month to month in a year (values are selected from Tables 5.5 and 5.7).

An over view of the scenarios which are applied in a standard day pattern is shown in next table:

Start in period (hours)	*Scenarios:* *water release scenarios* *ship movement scenarios* *turn around scenarios*	*Lane*	*Type of ship*	*Number of ships*	*Duration (hours)*
03:30 – 04:00	Water release Gatun Spillway Water use Gatun Power plant Water release Miraflores Spillway (including water for cooling)				
04:00 – 09:00	Pacific Ocean → Gatun Lake (uplockage)	West	Type I Type II Type III	1 1 3	5.0 5.5 6.0
04:00 – 09:00	Pacific Ocean → Gatun Lake (uplockage)	East	Type I Type II Type III	1 1 3	5.0 5.5 6.0
04:00 – 09:00	Atlantic Ocean → Gatun Lake (uplockage)	West	Type I Type II Type III	1 1 3	1.0 1.5 2.0
04:00 – 09:00	Atlantic Ocean → Gatun Lake (uplockage)	East	Type I Type II Type III	1 1 3	1.0 1.5 2.0
09:00 – 10:00	Turn around Pacific side (northbound to southbound)	West & East			
09:00 – 10:00	Turn around Atlantic side (southbound to norhbound)	West & East			
07:00 – 11:30	Gatun Lake → Pacific Ocean (downlockage)	West	Type I Type II Type III	1 1 3	5.0 5.5 6.0
07:00 – 11:30	Gatun Lake → Pacific Ocean (downlockage)	East	Type I Type II Type III	1 1 3	5.0 5.5 6.0
11:00 – 16:00	Gatun Lake → Atlantic Ocean (downlockage)	West	Type I Type II Type III	1 1 3	1.0 1.5 2.0
11:00 – 16:00	Gatun Lake → Atlantic Ocean (downlockage)	East	Type I Type II Type III	1 1 3	1.0 1.5 2.0
16:00 – 17:00	Turn around Pacific side (southbound to northbound)	West & East			
16:00 – 17:00	Turn around Atlantic side (northbound to southbound)	West & East			
17:30 – 19:30	Pacific Ocean → Gatun Lake (uplockage)	West	Type I Type II	3 1	5.0 5.5
17:30 – 19:30	Pacific Ocean → Gatun Lake (uplockage)	East	Type I Type II	3 1	5.0 5.5
17:30 – 19:30	Atlantic Ocean → Gatun Lake (uplockage)	West	Type I Type II	3 1	1.0 1.5
17:30 – 19:30	Atlantic Ocean → Gatun Lake (uplockage)	East	Type I Type II	3 1	1.0 1.5
20:00 – 20:30	Turn around Pacific side (northbound to southbound)	West & East			
20:00 – 20:30	Turn around Atlantic side (southbound to northbound)	West & East			

17:00 – 19:00	Gatun Lake → Pacific Ocean (downlockage)	West	Type I Type II	3 1	5.0 5.5
17:00 – 19:00	Gatun Lake → Pacific Ocean (downlockage)	East	Type I Type II	3 1	5.0 5.5
21:00 – 23:00	Gatun Lake → Atlantic Ocean (downlockage)	West	Type I Type II	3 1	1.0 1.5
21:00 – 23:00	Gatun Lake → Atlantic Ocean (downlockage)	East	Type I Type II	3 1	1.0 1.5
23:30 – 24:00	Turn around Pacific side (southbound to northbound)	West & East			
23:30 – 24:00	Turn around Atlantic side (northbound to southbound)	West & East			

Table 6.1 Scenarios in a standard day pattern

The standard day pattern has been used to build cases for validation. Different day patterns have been used in test cases.

6.3 Exchange coefficients

6.3.1 Method

As explained in Chapter 5 salt exchange coefficients are used in the numerical model. The exchange coefficients are derived using the results of the wet-season and dry season salinity measurements, and the results of some Delft3D computations, while also the results of simulations with the numerical model have been used to adjust the initially selected salt exchange coefficients. Maximum and minimum values of the salt exchange coefficients are found from a theoretical analysis.

The following notation is used in the derivation in next sections, similar as in Section 5.8:

water level: h (in m to PLD)
water depth: d (in m)
water volume: V (in m^3)
reference water volume: V_{ref} (in m^3); this volume is used in the salt balance
ship volume: S (in m^3, water displacement of the ship)
horizontal lock area: A (in m^2)
floor or sill level: f (in m to PLD)
salt concentration: c (in parts per thousand or kg salt per m^3 water; average value for considered water volume)
exchange coefficient: e_x (-)
salt exchange: SE (kg)

subscripts:
high: high basin
low: low basin

The lockage process is simulated in the numerical model as a series of subsequent steps. Both the water flows and the salt flows are computed in a step. Values at the beginning of a step are indicated with subscript 1, values at the end of a step are indicated with subscript 2. Salt concentrations in the salt balance are volume-averaged values (in basins); the salt concentration multiplied by the water volume represents a certain quantity of salt. The salt exchange (SE) in the salt balance represents the quantity of salt (in kg) that is transferred from one basin to another. The salt exchange SE is expressed as the product of a well-defined reference volume V_{ref}, a salt concentration (or salt concentration difference) related to this reference volume, and an exchange coefficient e_x. For full details reference is made to Section 5.8. The various steps during uplockage and downlockage for ships sailing from Pacific Ocean to Gatun Lake and reverse and ships sailing from Atlantic Ocean to Gatun Lake and reverse are shown in Figures 6.5 – 6.8.

In several phases of the lockage process the salt exchange is dependent on the presence of a ship in one of the considered basins, and on the dimensions of the ship. In these cases the salt exchange coefficient e_x is thus a function of the water displacement S of the ship. In the next analysis salt exchange coefficients are presented as a function of the ratio S/V_{ref}.

The dimensions of lock chambers, forebays and tailbays, as well as high and low water levels in the various basins are required in the theoretical analysis of maximum and minimum values of the exchange coefficient. The nominal length (about 330 m, see Table 2.2) and width of 33.5 m is selected for all lock chambers; forebays and tailbays have an arbitrarily length of 330 m and a width of 33.5 m. The selected high and low water levels in basins, floor levels of lock chambers, and sill levels of forebays and tailbays are shown in Table 6.2. The quantity Δh represents the water-level difference between high water in one basin and low water in the adjacent basin. High and low water levels in lock chambers and water levels in lakes and tailbays at the seaside are mean values.

	low level in basin (m to PLD)	*step in water level (m)*	*high level in basin (m to PLD)*	*Δ h (m)*	*floor level lock (m to PLD)*	*sill level tailbay or forebay (m to PLD)*
Tailbay Pacific Ocean	0.30		0.30			-15.24
Lock A	0.30	0.00	8.45	8.15	-15.54	
Lock B	8.45	8.15	16.60	16.30	-6.20	
Forebay Miraflores Lake	16.60	8.15	16.60	8.15		3.45
Tailbay Miraflores Lake	16.60		16.60			3.96
Lock C	16.60	0.00	25.90	9.30	3.35	
Forebay Gatun Lake	25.90	9.30	25.90	9.30		11.38
Forebay Gatun Lake	25.90	8.60	25.90	8.60		11.38
Lock F	17.30	8.60	25.90	17.20	4.17	
Lock E	8.70	8.60	17.30	17.20	-4.67	
Lock D	0.10	0.00	8.70	8.60	-13.51	
Tailbay Atlantic Ocean	0.10		0.10			-12.90

Table 6.2 Mean water levels in basins

The average water depth in lock chambers (above floor), forebays and tailbays (above sill) and the corresponding water volumes are computed from these quantities; the computed values are shown in Table 6.3.

Table 6.4 presents the average value of water-level difference Δh and the quantity of drain water that is required to equalize water levels in adjacent basins. A distinction is made for the following combinations of basins: tailbay sea – lock chamber, lock chamber – lock chamber, lock chamber – forebay in lake, and tailbay in lake – lock chamber.

	lock; low water level	*lock; high water level*	*tailbay seaside*	*forebay lake side*	*tailbay lake side*
average water depth (m)	13.98	22.54	14.27	14.06	12.64
average water volume (m^3)	154494	249198	157755	155470	139735

Table 6.3 Mean water depth and mean water volume of basins

		sea-lock	*lock-lock*	*lock-lake*	*lake-lock*
uplockage	average Δh (m)	8.38	16.90	8.68	9.30
uplockage	average drain volume (m^3)	92586	93415	95994	102812
downlockage	average Δh (m)	8.38	16.90	9.30	8.68
downlockage	average drain volume (m^3)	92586	93415	102812	95994

Table 6.4 Mean water-level difference Δh and mean volume of drain water

On the basis of salinity measurements in wet and dry season exchange coefficients have been derived for the various configurations of tailbays, locks and forebays (see Section 5.8 for explanation of method). In some situations it appeared, however, that the exchange coefficients displayed a lot of scatter; several of the derived coefficients were even beyond the upper and lower limits, which were obtained through the theoretical analysis.

There are several reasons for the scatter in results:

- measurements in adjacent basins, which are combined to derive exchange coefficients, were executed at different days and at different moments in a series of uplocking or downlocking ships (the history of successive ships and the dimensions of these ships are of importance)
- in the case of density waves in lock chambers the average salt concentration is difficult to determine on the basis of salinity profiles, which were taken one after another at different locations in the lock chamber
- measurements which were done in a lock chamber when a vessel was inside, were necessarily limited to the free space at the stern or the bow of the vessel and may not be representative for the full lock chamber
- measurements which were done in tailbays and forebays (which are in open connection with lake or sea entrance) may not always be representative for the average concentration in tailbay or forebay

- in the case of small salinity values such as in the higher lock chambers of Gatun Locks and Pedro Miguel Locks, combination of results may lead to a relatively great variation of the exchange coefficient.

Most reliable results have been obtained through analysis of the measurements in the empty lock chambers (phases 4 and 5) together with measurements in the outflow during spilling of water. Measurements near intakes, in locks with ship, and in forebays and tailbays are less representative and give less reliable results.
In general, the theoretical upper and lower limits for the exchange coefficients appeared very useful to estimate a realistic value for the exchange coefficient, together with the experiences and insights obtained through the measurements. In addition, some computations have been made for step II with the numerical flow program Delft3D; the results of these computations sustained the choice of representative exchange coefficients.

6.3.2 Exchange coefficients 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)
II the lock gates are opened and the ship moves from low basin to high basin; next the gates are closed again

Salt exchange coefficients e_x are derived for basic steps I and II in the uplockage process for various combinations of adjacent basins (tailbay sea – lock chamber, lock chamber – lock chamber, lock chamber – forebay in lake, and tailbay in lake – lock chamber). To that purpose the equations which describe the salt balance are used (see also Section 5.8).
A positive value of the exchange coefficient corresponds with a transfer of salt from high basin to low basin in step I. Starting from the assumption 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, a positive value of the exchange coefficient corresponds with a transfer of salt from low basin to high basin in step II. But as a result of the water displacement of the ship a net salt transfer may occur from high basin to low basin.

Uplockage, step I

The water level in the low basin (with ship) is equalized with the water level in the high basin (without ship).

Maximum and minimum value of exchange coefficients, uplockage step I

The derivation of maximum and minimum exchange coefficients is similar for next three basin configurations:

low basin = tailbay sea side, high basin =lock
low basin = lock, high basin = lock
low basin = tailbay lake side, high basin = lock

Salt balance:

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

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

An upper limit is found for the exchange coefficient when we assume that all salt in the high basin is transferred to the low basin. This requires that the salt is concentrated in the water body near the openings in the floor of the lock chamber. Full transfer of salt results in the condition $c_{high2} = 0$ at the end of step I.

Substitution of $c_{high2} = 0$ in the salt balance yields:

$$e_{x\text{-}max} = \frac{V_{high1}}{V_{ref}}$$

Minimum exchange occurs when no salt is transferred from high basin to low basin. However, this seems not realistic for a lock emptying system with openings in the floor of the lock chamber (the saltier water is always near the floor). In a more realistic approach we assume that mimimum exchange occurs when the water in the high basin (= lock chamber) is fully mixed up prior to emptying. This results in: $c_{high2} = c_{high1}$.

Substitution of $c_{high2} = c_{high1}$ in the salt balance yields:

$$e_{x\text{-}min} = 1$$

low basin = lock, high basin = forebay lake side

Salt balance:

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

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

An upper limit is found for the exchange coefficient when we assume that the salt concentration in the forebay becomes zero after the withdrawal of water. Since the total water volume of the forebay is not effected by the withdrawal of water (the withdrawn water is immediately replenished by an equal quantity of water from the lake), we implicitly assume that the supplied water from the lake has also a zero salinity ($c_{lake1} = 0$) .

Substitution of $c_{high2} = 0$ and $c_{lake1} = 0$ in the salt balance yields:

$$e_{x\text{-}max} = \frac{V_{high1}}{V_{ref}}$$

A lower limit is found when we assume that no salt is transferred from the forebay to the lock. This assumption seems realistic considering that the earlier intruded saltier water may concentrate in (deeper) areas of the forebay, far away from the water intakes in centre wall and side wall. We than find:

$e_{x\text{-}min} = 0$

Upper and lower limits for the exchange coefficient in step I of the uplockage process are shown in Figures 6.1a – 6.1d versus the ratio S/V_{ref} (note: the water displacement S of the ship does not play a role in step I, but this quantity is of importance in the other steps).

Selected values of exchange coefficients in simulations, uplockage step I

On the basis of measurements in wet and dry season exchange coefficients have been derived for various configurations of tailbays, locks and forebays; the results have been plotted in Figures 6.1a – 6.1d. It appears that the scatter in results is quite considerably, and that some of the derived coefficients are beyond upper or lower limit.
In step I water is withdrawn from the high basin (without ship) and spilled in the low basin (with ship). Generally, after exit of the previous ship, salinity gradients are present in the high basin both in vertical and horizontal direction. Fill water is withdrawn from the lower water region near the floor of the high basin and has a higher than average salt concentration ($e_x > 1$). In the case that the high basin is a forebay fill water is withdrawn through intakes in centre wall and side wall; the withdrawn water has not necessarily a higher salinity than the average salinity of the forebay.
Measurements which were executed in the empty lock chambers and in the outflow during emptying of the lock chambers, have been used to derive the exchange coefficient for the configurations 'sea-lock', 'lock-lock' and 'lake-lock' (the high basin is a lock); an average exchange coefficient $e_x = 1.3$ was found. This average value is also applied in the numerical simulation model. For the configuration 'lock-lake' (the high basin is a forebay in the lake) a smaller value $e_x = 0.95$ has been selected; this choice is based on the results of the measurements.
The selected values are independent of the ratio S/V_{ref}; they are plotted as a grey line in Figures 6.1a – 6.1d.

Uplockage, step II

The lock gates are opened and the ship moves from low basin to high basin; next the gates are closed again.

Maximum and minimum value of exchange coefficients, uplockage step II

low basin = tailbay sea side, high basin =lock

salt balance:

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

where
$V_{high2} = V_{high1} - S$
$V_{ref} = V_{high1}$

Salt water intrudes the lock chamber as a result of density currents and movement of the ship. An upper limit is found for the exchange coefficient when we assume that the salt concentration in the lock at the end of step II has become equal to the salt concentration in the tailbay; we also assume that the salt concentration in the tailbay does not reduce (this is a conservative assumption). Consequently, $c_{low2} = c_{low1} = c_{tailbay}$, and $c_{high2} = c_{low2}$.

Substitution of $c_{high2} = c_{low2} = c_{low1}$ in the salt balance yields:

$$e_{x\text{-max}} = \frac{(V_{high1} - S)}{V_{high1}} = \left(1 - \frac{S}{V_{ref}}\right)$$

For S = 0 we find: $e_{x\text{-max}} = 1$.

A lower limit would be found for the exchange coefficient when the following was assumed: (i) all salt in the lock chamber is concentrated in the water that is pushed out by the moving ship, and (ii) the inflow of salt water from the tailbay is prevented by this outflow. This would reduce the salt concentration in the lock chamber to zero ($c_{high2} = 0$).
However, the assumption of zero salinity in the lock chamber at the end of step II is not realistic, in particular in the case of smaller ships. Density currents will occur causing salt intrusion. Moreover, since there is no upward step in the floor at the entrance of the lock, the intrusion of salt water from the tailbay is not hampered.
A more realistic lower limit is found when we assume that the concentration in the lock chamber remains unchanged during entry of a ship. This requires that the return current (outflowing water) has the same average concentration as the water in the lock chamber at the start of step II. The inflow of saltier water prior, during and after the ship movement is prevented. This leads to the condition $c_{high2} = c_{high1}$ at the end of step II and we find:

$e_{x\text{-min}} = 0$

low basin = lock, high basin = lock

salt balance:

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

and

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

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

An upper limit for the exchange coefficient is found when we assume that the salt concentration in the high lock at the end of step II, after movement of the ship from low lock to high lock, has become equal to the salt concentration in the low lock. The assumption that the salt concentration in the high lock becomes greater than the salt concentration in the low lock is not realistic, in particular because of the upward step in the floor. An equal concentration leads to the condition $c_{high2} = c_{low2}$ at the end of step II.

Substitution of $c_{high2} = c_{low2}$ in the salt balance yields:

$$e_{x\text{-max}} = \frac{V_{low1} \cdot (V_{high1} - S)}{V_{high1} \cdot (V_{low1} + V_{high1})} = \left(1 - \frac{S}{V_{ref}}\right) \cdot \left(\frac{V_{low1}}{V_{low1} + V_{high1}}\right)$$

For S = 0 we find:

$$e_{x\text{-max}} = \frac{V_{low1}}{(V_{low1} + V_{high1})}$$

A lower limit is found for the exchange coefficient when - in a conservative approach – is assumed that (i) all salt in the high lock is concentrated in the water that is pushed out to the low lock by the moving ship (outflow over the downward step in the floor), (ii) all salt in the low lock is concentrated in the water volume below the level of the step, and (iii) density-driven inflow of water in the high lock is prevented both by the upward step in the floor and the return current of the ship. Consequently, the salt concentration in the high lock reduces to zero ($c_{high2} = 0$) at the end of step II.

Substitution of $c_{high2} = 0$ in the salt balance yields:

$$e_{x\text{-min}} = -\left(1 - \frac{S}{V_{ref}}\right) \cdot \frac{c_{high1}}{(c_{low1} - c_{high1})}$$

A conservative estimate for the value of the term $c_{high1} / (c_{low1} - c_{high1})$ is 0.5, assuming $c_{low1} = 3.c_{high1}$. For S = 0 we find:

$e_{x\text{-min}} = -0.5$

low basin = lock, high basin = forebay lake side

salt balance:

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

and

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

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

The 'lock-lake' configuration is geometrical similar with the 'lock-lock' configuration because of the upward step in the floor between lock and forebay. In the upper and lower limit approach we assume that the ship remains in the forebay. The term ($S \cdot c_{lake1}$) in the salt balance disappears, and the relationship $V_{high2} = V_{high1}$ is replaced by the relationship $V_{high2} = V_{high1} - S$. Upper and lower limits for the exchange coefficient are than found assuming $c_{high2} = c_{low2}$ in the upper limit approach and $c_{high2} = 0$ in the lower limit approach, similar as for the 'lock-lock' configuration. This results in:

$$e_{x\text{-}max} = \left(1 - \frac{S}{V_{ref}}\right) \cdot \left(\frac{V_{low1}}{V_{low1} + V_{high1}}\right)$$

$$e_{x\text{-}min} = -\left(1 - \frac{S}{V_{ref}}\right) \cdot \frac{c_{high1}}{(c_{low1} - c_{high1})}$$

A conservative estimate for the value of the term $c_{high1} / (c_{low1} - c_{high1})$ is 0.5.

low basin = tailbay lake side, high basin = lock

salt balance:

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

where
$V_{high2} = V_{high1} - S$
$V_{ref} = V_{high1}$

The 'lake-lock' configuration is geometrical similar with the 'sea-lock' configuration (no upward step in the floor at the entrance to the lock). An upper limit for the exchange coefficient is found when we assume that the salt concentration in the lock has become equal to the salt concentration in the tailbay at the end of step II ($c_{high2} = c_{low2}$). When we also assume that the salt concentration in the tailbay is not effected by the movement of the ship (conservative assumption, $c_{low2} = c_{low1}$), we find - similar as for the 'sea-lock' configuration - as upper limit:

$$e_{x\text{-}max} = \frac{V_{high1} - S}{V_{high1}} = \left(1 - \frac{S}{V_{ref}}\right)$$

A lower limit is found when we assume that density flows do not occur and that the return current of the ship has an equal average concentration as the water in the lock chamber. This

leads to the condition $c_{high2} = c_{high1}$ at the end of step II and we find, similar as for the 'sea-lock' configuration:

$$e_{x\text{-}min} = 0$$

Upper and lower limits for the exchange coefficient in step II of the uplockage process are shown in Figure 6.2a – 6.2d versus the ratio S/V_{ref}.

Selected values of exchange coefficients in simulations, uplockage step II

The 'sea-lock' configuration and the 'lake-lock' configuration are geometrical similar (they both miss an upward step in the floor at the entrance to the lock). This means that density currents are likely to occur when the gates are opened, in particular when small ships are involved. However, density currents between tailbay lake and locks (at Pedro Miguel) are much weaker than density currents between tailbay sea and the lower Pacific locks of Miraflores or the lower Atlantic locks of Gatun. This is caused by the lower salinity values at Pedro Miguel and, consequently, the lower density differences and lower velocities of the density currents (the propagation speed of the density current is proportional to the square root of $\Delta\rho/\rho$ (ρ = density, $\Delta\rho$ = density difference).
Another difference is that the downstream gates of the lower locks of Miraflores are opened far before the arrival of a next vessel (this is a normal operation rule, see Section 3.3). This means that the lock chamber for the greater part is filled with water from the sea entrance prior to entry of the ship. For the configuration 'sea → Lock A' at the Pacific side we estimate an average value of 0.9 for the exchange coefficient at $S/V_{ref} = 0$ (a value of 1.0 corresponds to a full exchange with salt water from the tailbay).
The downstream gates of the lower locks at Gatun are opened when a ship has approached the centre wall. In general it takes about 5 - 10 minutes before the ship enters. This time is sufficient for the development of a strong exchange flow; as a result a considerable part of the water in the lock chamber is replaced with salt water from the tailbay. Probably, the exchanged quantity is smaller than the exchanged quantity in the lower Miraflores locks at the Pacific side. For that reason we apply a somewhat smaller exchange coefficient ($e_x = 0.7$ at $S/V_{ref} = 0$) for the configuration 'sea → Lock D'.
We put that the exchange coefficients reduce linearly in dependence of the ratio S/V_{ref}. The selected exchange functions are shown in Figure 6.2a. as grey lines. The exchange coefficient which was derived from the measurements is also plotted in Figure 6.2a, but is far above the upper limit (see Section 6.3.1 for probable reasons).

The downstream gates of Pedro Miguel Locks ('lake-lock' configuration) are operated in the same way as the downstream gates of the lower locks of Gatun. As discussed before the lesser density difference causes weaker density flows. Also in view of the results of the simulation runs we have selected the lower limit value for the exchange coefficient (e_x = 0.05 for all ratios of S/V_{ref}), see Figure 6.2d.

The 'lock-lock' configuration is geometrical similar with the 'lock-lake' configuration (upward step at the entrance to the high basin). Taking into account the results of the measurements and the results of simulations for these configurations, and considering the blocking effect of the upward step in the floor, we have selected small values for the exchange

coefficient for the lower steps and - in view of lesser density differences - zero exchange coefficients for the higher steps. This means that, apart from the salt transfer corresponding with the exchange of the ship's volume from high lock to low lock, some salt respectively no salt is transferred to the higher lock. The selected exchange coefficients are:

Lock A → Lock B; Lock D → Lock E; $e_x = 0.05$ at $S/V_{ref} = 0$
Lock B → forebay; Lock E → Lock F; $e_x = 0.0$ at $S/V_{ref} = 0$
Lock C → forebay; Lock F → forebay; $e_x = 0.0$ at $S/V_{ref} = 0$

Again, we put that the exchange coefficients reduce linearly with the ratio S/V_{ref}, see Figures 6.2b and 6.2c. The points which were obtained from the measurements, are also shown in these figures. Generally, they are higher than the selected values; some of them are beyond the limit lines; these values are excluded from the analysis.

Computations have been made with our Delft3D numerical programme for step II, uplockage, for the case with initial concentrations c_{low1} = 10 ppt and c_{high1} is 2 – 4 ppt (linear increase from water surface to bottom). The selected initial concentration values may be representative for the configurations 'Lock A → Lock B' and 'Lock D → Lock E'. The ship (ship type III, S = 90,000 m^3) moves in 10 minutes from lower lock to higher lock. The computed exchange coefficient e_x and the computed volume-averaged salt concentrations of upper and lower lock are presented in Figure 6.9a as a function of time. The figure is valid for $S/V_{ref} = 0.58$. The exchange coefficient varies with time and is a function of the density differences between the two basins; the graph demonstrates that the exchange coefficient fluctuates in dependence of density waves, which travel in both lock chambers. After the ship has entered the lower lock (after 10 minutes) the exchange coefficient has a value of 0.01. The reduction factor ($1-S/V_{ref}$) which is applied in the simulation model (see Section 5.8.1), amounts to 0.42, giving $e_x = 0.02$ at $S/V_{ref} = 0$.
The validation runs indicated however, that $e_x = 0.05$ at $S/V_{ref} = 0$ is a better choice. The latter value was finally used in the validation. Nevertheless, the Delft3D results demonstrate that the exchange coefficient in step II, uplockage, 'lock – lock', has a relatively small value.

6.3.3 Exchange coefficients downlockage

Two basic steps can be distinguished in the uplockage process:

I the water level in the low basin (without ship) is equalized with the water level in the high basin (with ship)

II the lock gates are opened and the ship moves from high basin to low basin; next the gates are closed again

Salt exchange coefficients e_x are derived for basic steps I and II in the downlockage process for various combinations of adjacent basins (forebay in lake – lock chamber, lock chamber – tailbay in lake, lock chamber – lock chamber, and lock chamber – tailbay in sea). To that purpose the equations which describe the salt balance are used (see also Section 5.8).
A positive value of the exchange coefficient corresponds with a transfer of salt from high basin to low basin in step I. Starting from the assumption 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, a positive value of the exchange coefficient corresponds with a transfer of salt

from low basin to high basin in step II. The water displacement of the ship causes an additional salt transfer from low basin to high basin.

Downlockage, step I

The water level in the low basin (without ship) is equalized with the water level in the high basin (with ship).

Maximum and minimum value of exchange coefficients, downlockage step I

The derivation of maximum and minimum exchange coefficients is similar for next three basin configurations:

high basin = lock, low basin = tailbay lake side
high basin = lock, low basin = lock
high basin =lock, low basin = tailbay sea side

Salt balance:

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

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

An upper limit is found for the exchange coefficient when we assume that all salt in the high basin is transferred to the low basin. Full transfer of salt results in the condition $c_{high2} = 0$ at the end of step I.

Substitution of $c_{high2} = 0$ in the salt balance yields:

$$e_{x\text{-}max} = \frac{V_{high1}}{V_{ref}}$$

The water volume V_{high1} is dependent on the dimensions of the ship and $e_{x\text{-}max}$ is thus a function of S/V_{ref}.

Minimum exchange occurs when no salt is transferred from high basin to low basin. However, this seems not realistic for a lock emptying system with openings in the floor of the lock chamber (the saltier water is always near the floor, under the ship). In a more realistic approach we assume that mimimum exchange occurs when the water in the high lock chamber is fully mixed up prior to emptying. This results in: $c_{high2} = c_{high1}$.

Substitution of $c_{high2} = c_{high1}$ in the salt balance yields:

$$e_{x\text{-}min} = 1$$

high basin = forebay lake side, low basin = lock

salt balance:

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

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

An upper limit is found for the exchange coefficient when we assume that the salt concentration in the forebay becomes zero after the withdrawal of water. Since the total water volume of the forebay is not effected by the withdrawal of water (the withdrawn water is immediately replenished by an equal quantity of water from the lake), we implicitly assume that the supplied water from the lake has also a zero salinity ($c_{lake1} = 0$).

Substitution of $c_{high2} = 0$ and $c_{lake1} = 0$ in the salt balance yields:

$$e_{x\text{-}max} = \frac{V_{high1}}{V_{ref}}$$

In this case V_{high1} is not dependent on the dimensions of the ship.

A lower limit is found when we assume that no salt is transferred from the forebay to the lock. This assumption seems realistic considering that the earlier intruded saltier water may concentrate in (deeper) areas of the forebay, far away from the water intakes in centre wall and side wall. We than find:

$$e_{x\text{-}min} = 0$$

Upper and lower limits for the exchange coefficient in step I of the downlocking process are shown in Figures 6.3a – 6.3d versus the ratio S/V_{ref}.

Selected value of exchange coefficients in simulations, downlockage step I

In step I water is withdrawn from the high basin (with ship) and spilled in the low basin (without ship). Before the entry of a ship, the water in the high basin has been mixed up during filling and the salinity has become rather uniform in the high basin. When the ship enters, this uniform salinity distribution is disturbed, but less than in the case of a ship that exits (uplockage). Water that is subsequently withdrawn from the high basin may have a higher salinity than the average salinity in the high basin ($e_x > 1$), but the deviation from $e_x = 1$ is less than in the case of uplockage. When the high basin is a forebay there was no mixing up and the withdrawn water may have a lesser than average salinity ($e_x < 1$), similar as for uplockage.

Measurements which were executed in the empty lock chambers and in the outflow have been used to derive the exchange coefficient for the configurations 'lock-sea', 'lock-lock'

and 'lock-lake' (the high basin is a lock), but also the salinity in the high basin (with ship) was required in the analysis; because measurements in a basin with ship are less representative, the derived exchange coefficients display a large scatter, and a number of them is even beyond upper or lower limit lines (see Figures 6.3a, 6.3b and 6.3d). Taking also into account the results for uplockage, we have selected an average exchange coefficient $e_x = 1.2$ for these three configurations, a little smaller than in the case of uplockage.

For the configuration 'lake-lock' (the high basin is a forebay in the lake) a smaller value $e_x = 0.85$ has been selected; this choice is based on the results of the measurements and validation runs.

All selected values are independent of the ratio S/V_{ref}; they are plotted as a grey line in Figures 6.3a – 6.3d.

Downlockage, step II

The lock gates are opened and the ship moves from high basin to low basin; next the gates are closed again.

Maximum and minimum value of exchange coefficients, downlockage step I

high basin = forebay lake side, low basin = lock

salt balance:

$$SE = (V_{high2} \cdot c_{high2}) - (V_{high1} \cdot c_{high1}) = (e_x \cdot V_{ref} \cdot (c_{low1} - c_{high1})) + (S \cdot c_{low1}) - (S \cdot c_{forebay1})$$

and

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

where

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

In the previous step I the water in the lock was equalized with the water in the forebay and mixed up. This resulted in a more or less uniform salinity in the lock. In the present step II the ship moves from forebay (high basin) to lock (low basin) and salt water is transferred because of the movement of the ship and density differences between the two basins. In the upper and lower limit approach we assume that the water quantity S (equal to the volume of the ship) is not immediately transferred from the forebay to the lake. The term $(S \cdot c_{forebay1})$ in the salt balance disappears, and the relationship $V_{high2} = V_{high1}$ is replaced by the relationship $V_{high2} = V_{high1} + S$. An upper limit is found for the exchange coefficient when we assume that the salt concentration in the forebay at the end of step II has become equal to the salt concentration in the lock. This leads to the condition $c_{high2} = c_{low2}$ at the end of step II.

Substitution of $c_{high2} = c_{low2}$ in the salt balance yields:

$$e_{x\text{-}max} = \frac{(V_{high2} - S) \cdot (V_{low1} - S)}{V_{high2} \cdot (V_{low1} + V_{high1})} = \left(1 - \frac{S}{V_{ref}}\right) \cdot \left(\frac{V_{low2}}{V_{low1} + V_{high1}}\right)$$

For S = 0 we find:

$$e_{x\text{-}max} = \frac{V_{low2}}{(V_{low1} + V_{high1})}$$

In a lower limit approach for the exchange coefficient it is reasonable to assume that - apart from the water displacement caused by the ship - no additional salt water is transferred from lock to forebay. This results in:

$e_{x\text{-}min} = 0$

high basin = lock, low basin = lock

salt balance:

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

and

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

The derivation of upper and lower limits for the exchange coefficient is similar as for the configuration 'lake-lock'. We find:

$$e_{x\text{-}max} = \left(1 - \frac{S}{V_{ref}}\right) \cdot \left(\frac{V_{low2}}{V_{low1} + V_{high1}}\right)$$

and

$e_{x\text{-}min} = 0$

high basin = lock, low basin = tailbay lake side
high basin =lock, low basin = tailbay sea side

salt balance:

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

where
$V_{high2} = V_{high1} + S$
$V_{ref} = V_{high2}$

An upper limit is found for the exchange coefficient when we assume that the salt concentration in the lock at the end of step II has become equal to the salt concentration in the tailbay. This leads to the condition $c_{high2} = c_{low2}$ at the end of step II. We also assume that the concentration in the tailbay does not reduce during exit of the ship (conservative assumption). This leads to the condition: $c_{low2} = c_{low1}$ at the end of step II.

Substitution of $c_{high2} = c_{low2} = c_{low1}$ in the salt balance yields:

$$e_{x\text{-max}} = \frac{(V_{high2} - S)}{V_{high2}} = \left(1 - \frac{S}{V_{ref}}\right)$$

For S = 0 we find: $e_{x\text{-max}} = 1$.

Again, a lower limit is found for the exchange coefficient when we assume that - apart from the water displacement caused by the ship - no additional salt water is transferred from tailbay to lock. This results in:

$e_{x\text{-min}} = 0$

Selected value of exchange coefficients in simulations, downlockage step II

The 'lock-sea' configuration and the 'lock-lake' configuration are geometrical similar (they both miss a downward step in the floor at the entrance to the tailbay). Density currents will occur when the gates are opened, in particular when small ships are involved.
The downstream gates of the locks are closed shortly after the ship has moved to the tailbay. The moving ship causes an inflow of saltier water from the tailbay. In addition, some extra saltier water may enter, but because of the relative short opening time of the gates, a full exchange of water is not plausible. We estimate a value $e_x = 0.4$ at $S/V_{ref} = 0$ for the 'lock-sea' configuration ($e_x = 1$ means that the salt concentration in the lock becomes equal to the salt concentration in the tailbay). For the 'lock-lake' configuration ('Lock C → tailbay') we select a value $e_x = 0.1$ at $S/V_{ref} = 0$. The reasons for this choice are: (i) salt concentrations and thus density differences and propagation velocities of density currents are smaller (the propagation speed of the density current is proportional to the square root of $\Delta\rho/\rho$, with ρ = density, $\Delta\rho$ = density difference), (ii) validation runs indicate that this is a best-suited choice.
The selected exchange functions are plotted in Figures 6.4a and 6.4d. The values which were derived from the measurements have also been plotted in these figures. It appears that these values are below the lower limit line. The main reason for these low values is the difficulty to measure representative salinity values in a lock chamber when a ship is inside and to measure representative salinities in tailbays, which are in open connection with lake or sea entrance (see also Section 6.3.1).

The 'lock-lock' configuration is geometrical similar with the 'lake-lock' configuration (downward step at the entrance to the low basin). The water in the lower basin is mixed up prior to entry of the ship and has a rather uniform salt concentration. Considering the blocking effect of the downward step, but a downward movement of the ship causing an upward return current, we have selected small positive values for the exchange coefficients. This means that, apart from the salt transfer corresponding with the exchange of the ship's volume from low lock to high lock, some additional salt is transferred to the higher lock.
In view of lesser density differences between lower adjacent basins than basins which are at a higher elevation, we differentiate the exchange coefficients as:

forebay → Lock C; forebay → Lock F; $e_x = 0.05$ at $S/V_{ref} = 0$
forebay → Lock B; Lock F → Lock E; $e_x = 0.10$ at $S/V_{ref} = 0$
Lock B → Lock A; Lock E → Lock D; $e_x = 0.15$ at $S/V_{ref} = 0$

We put that the exchange coefficients reduce linearly with the ratio S/V_{ref}, see Figures 6.4b and 6.4c. The points which were obtained from the measurements, are also shown in these figures. All measurement points are beyond upper and / or lower limit lines. Again, the difficulty to measure representative salinity values in locks with ships inside and representative salinity values in forebays is the main reason for this scatter in results.

Computations have been made with our Delft3D numerical programme for step II, down-lockage, for the case with initial concentrations $c_{low1} = 10$ ppt and c_{high1} is 2 – 4 ppt (linear increase from water surface to bottom). The selected initial concentration values may be representative for the configurations 'Lock B → Lock A' and 'Lock E → Lock D'. The ship (ship type III, S = 90,000 m^3) moves in 10 minutes from higher lock to lower lock. Together with the exchange coefficient e_x the computed volume-averaged salt concentrations of upper and lower lock are plotted in Figure 6.9b. The figure is valid for $S/V_{ref} = 0.58$. The graph demonstrates that the exchange coefficient e_x is a function of time and fluctuates in dependence of density waves, which travel in both lock chambers. After the ship has entered the lower lock (after 10 minutes) the exchange coefficient has a value of 0.04. The reduction factor ($1-S/V_{ref}$), which is applied in the simulation model (see Section 5.8.2), amounts to 0.42, giving $e_x = 0.095$ at $S/V_{ref} = 0$. The Delft3D computations sustain the above choice of $e_x = 0.15$ at $S/V_{ref} = 0$.

6.3.4 Exchange coefficients used in the simulation model

The final exchange coefficients which are used in the simulation model in validation runs for the existing situation, are shown in next tables. The coefficients are used both in ship-movement scenarios and turn-around scenarios (in the latter case step I 'equalize water levels' is the only action; the exchange coefficients related to 'equalize water level' as well as the coefficients for time-dependent exchange of salt water between forebays/tailbays and lakes are applied).

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay sea	Lock A	Equalize water levels	1.3
Tailbay sea	Lock A	Move ship	0.9*
Lock A	Lock B	Equalize water levels	1.3
Lock A	Lock B	Move ship	0.05*
Lock B	Forebay ML-south	Equalize water levels	0.95
Lock B	Forebay ML-south	Move ship	0.0*
Forebay ML-south	Miraflores Lake	(Density flows)	1.0**
Miraflores Lake	Tailbay ML-north	(Density flows)	1.0**
Tailbay ML-north	Lock C	Equalize water levels	1.3
Tailbay ML-north	Lock C	Move ship	0.05*
Lock C	Forebay GL-south	Equalize water levels	0.95
Lock C	Forebay GL-south	Move ship	0.0*
Forebay GL-south	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 6.5 Uplockage. Pacific Ocean → Gatun Lake. West and East lane.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay GL-south	(Density flows)	1.0**
Forebay GL-south	Lock C	Equalize water levels	0.85
Forebay GL-south	Lock C	Move ship	0.05*
Lock C	Tailbay ML-north	Equalize water levels	1.2
Lock C	Tailbay ML-north	Move ship	0.1*
Tailbay ML-north	Miraflores Lake	(Density flows)	1.0**
Miraflores Lake	Forebay ML-south	(Density flows)	1.0**
Forebay ML-south	Lock B	Equalize water levels	0.85
Forebay ML-south	Lock B	Move ship	0.10*
Lock B	Lock A	Equalize water levels	1.2
Lock B	Lock A	Move ship	0.15*
Lock A	Tailbay sea	Equalize water levels	1.2
Lock A	Tailbay sea	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 6.6 Downlockage. Gatun Lake → Pacific Ocean. West and East lane.

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay sea	Lock D	Equalize water levels	1.3
Tailbay sea	Lock D	Move ship	0.7*
Lock D	Lock E	Equalize water levels	1.3
Lock D	Lock E	Move ship	0.05*
Lock E	Lock F	Equalize water levels	1.3
Lock E	Lock F	Move ship	0.0*
Lock F	Forebay GL-north	Equalize water levels	0.95
Lock F	Forebay GL-north	Move ship	0.0*
Forebay GL-north	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 6.7 Uplockage. Atlantic Ocean → Gatun Lake. West and East lane.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay GL-north	(Density flows)	1.0**
Forebay GL-north	Lock F	Equalize water levels	0.85
Forebay GL-north	Lock F	Move ship	0.05*
Lock F	Lock E	Equalize water levels	1.2
Lock F	Lock E	Move ship	0.10*
Lock E	Lock D	Equalize water levels	1.2
Lock E	Lock D	Move ship	0.15*
Lock D	Tailbay sea	Equalize water levels	1.2
Lock D	Tailbay sea	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 6.8 Downlockage. Gatun Lake → Atlantic Ocean. West and East lane.

The exchange coefficients related to spillages, cooling water and hydropower generation are determined through the validation runs and are discussed in Section 6.5.

Spillage or other water release	*Exchange coefficient*
Miraflores Spillway (+cooling)	1.5
Gatun Spillway	7.5
Gatun Power Station	7.5

Table 6.9 Spillages and other water releases Miraflores Lake and Gatun Lake.

6.4 Testing of simulation model

We have checked the proper functioning of the simulation model by running several test cases. These test cases were such designed that results could be checked step by step. Different Coefficient Sets and Day Patterns have been used. Next table present an overview of the exchange coefficients which were applied in Coefficient Sets:

Coefficient Set	*Up equalize*	*Up ship*	*Down equalize*	*Down ship*	*Exchange with lakes*)*	*Water releases*
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0.1
c3	0	0	0	0	0	1.0
c4	0	0	0	0	1.0	0
c5	0	0	0	1.0	0	0
c6	0	0	1.0	0	0	0
c7	0	1.0	0	0	0	0
c8	1.0	0	0	0	0	0
c9	0	0.2	0	0.2	1.0	0
c10	0.5	0	0.5	0	1.0	0
c11	0.5	0.2	0.5	0.2	1.0	0
c12	0.5	0.2	0.5	0.2	0	0

*) e_{xfull}

Table 6.10 Overview of Coefficient Sets used in test cases

All test cases were run using Day Patterns consisting of only a single or a few scenarios (ship-movement scenarios, turn-around scenarios or water-release scenarios). Next table presents an overview of the Day Patterns which were applied in the test runs:

Day Pattern	*Scenarios in Day Pattern*	*Lane*
d1	ship movement Pac. > Atl.; ship type 0	West & East
d2	ship movement Pac. > Atl.; ship type III	West & East
d3	ship movement Pac. > Atl.; ship type I	West & East
d4	ship movement Pac. > Atl.; ship type II	West & East
d5	ship movement Atl. > Pac.; ship type 0	West & East
d6	ship movement Atl. > Pac.; ship type III	West & East
d7	Gatun Spillway; daily discharge 0 Gatun Power Station; daily discharge 0 Miraflores Spillway (+ cooling); daily discharge 0	-
d8	Gatun Spillway; daily discharge 5E6 m^3 Gatun Power Station; daily discharge 5E6 m^3 Miraflores Spillway (+ cooling); daily discharge 5E4 m^3	-
d9	turn around Pacific side N > S and S > N	West & East
d10	turn around Atlantic side S > N and N > S	West & East
d11	ship movement Pac. > Atl.; ship type III (2 ships, Δt = 15 min.)	East
d12	ship movement Pac. > Atl.; ship type III (2 ships, Δt = 30 min.)	West

Table 6.11 Overview of Day Pattern 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 tailbay) set on 0. The purpose of these tests was to check the handling of water levels, water volumes and water balance when ships move from ocean to ocean. Table 6.12 presents an overview of the test cases in this first series A.

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
1	c1	d1	Jan 1 – Jan 31, 2002	scenario	single ship, S = 0
1-R	c1	d5	Jan 1 – Jan 31, 2002	scenario	single ship, S = 0
2A	c1	d2	Jan 1 – Jan 31, 2002	scenario	single ship
2A-R	c1	d6	Jan 1 – Jan 31, 2002	scenario	single ship
2B	c1	d3	Jan 1 – Jan 31, 2002	scenario	single ship
2C	c1	d4	Jan 1 – Jan 31, 2002	scenario	single ship

Table 6.12 Test cases series A: initial salt concentrations in all basins are zero

Some results of Test case 1 (single ship movement from Pacific to Atlantic Ocean each day, ship volume S = 0) are presented in Figures TC1-1, TC1-2 and TC1-3 as an example. Note that results are shown at the end of each scenario.

Conclusions Test series A:

From the test runs we conclude: Computation of tidal movements at the seaside of the locks, water levels of lakes, water levels and volumes of lock chambers, forebays and tailbays is correct. Water movements caused by uplocking or downlocking ships are exact simulated and fulfil the water balance.

Test series B

A second series of tests was focused on the proper functioning of spillways, handling of water balance and salt balance, use of coefficients, time-dependent exchange of salt water between forebays / tailbays and lakes and salt-migration process. The initial salt concentration in all basins was set on 0 (including Pacific and Atlantic tailbay), but the initial salt concentration of Gatun Lake and Miraflores Lake was set on 30 ppt. Table 6.13 presents an overview of test cases in series B:

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
3A	c3	d8	Jan 1 – Dec 31, 2002	scenario	water releases
3B	c1	d8	Jan 1 – Dec 31, 2002	scenario	water releases
3C	c3	d7	Jan 1 – Dec 31, 2002	scenario	water releases
3D	c2	d8	Jan 1 – Dec 31, 2002	scenario	water releases
4A	c4	d1	Jan 1 – Jan 7, 2002	scenario	exchange with lakes
4A-R	c4	d5	Jan 1 – Jan 7, 2002	scenario	exchange with lakes
4B	c4	d2	Jan 1 – Jan 7, 2002	scenario	exchange with lakes
4B-R	c4	d6	Jan 1 – Jan 7, 2002	scenario	exchange with lakes

4C	c1	d1	Jan 1 – Jan 7, 2002	scenario	exchange with lakes
4C-R	c1	d5	Jan 1 – Jan 7, 2002	scenario	exchange with lakes
4D	c4	d11	Jan 1 – Jan 7, 2002	scenario	exchange with lakes
4E	c4	d12	Jan 1 – Jan 7, 2002	scenario	exchange with lakes
5A	c1	d9	Jan 1 – Jan 2, 2002	scenario	turn around Pacific side
5B	c1	d10	Jan 1 – Jan 2, 2002	scenario	turn around Atlantic side
5C	c10	d9	Jan 1 – Jan 2, 2002	scenario	turn around Pacific side
5D	c10	d10	Jan 1 – Jan 2, 2002	scenario	turn around Atlantic side
6A	c8	d2	Jan 1 – Jan 7, 2002	scenario	use of coefficients
6A-R	c8	d6	Jan 1 – Jan 7, 2002	scenario	use of coefficients
6B	c7	d2	Jan 1 – Jan 7, 2002	scenario	use of coefficients
6B-R	c7	d6	Jan 1 – Jan 7, 2002	scenario	use of coefficients
6C	c6	d2	Jan 1 – Jan 7, 2002	scenario	use of coefficients
6C-R	c6	d6	Jan 1 – Jan 7, 2002	scenario	use of coefficients
6D	c5	d2	Jan 1 – Jan 7, 2002	scenario	use of coefficients
6D-R	c5	d6	Jan 1 – Jan 7, 2002	scenario	use of coefficients

Table 6.13 Test cases series B: initial salt concentrations in Gatun Lake and Miraflores Lake 30 ppt, initial salt concentrations in all other basins zero

Some results of Test cases 3A and 3B are shown in Figures TC3A-1, TC3A-2 and TC3B-1 as an example. These test cases concern the functioning of the water-release scenarios. Water is released from the lakes, but the water level remains as prescribed (the prescribed water levels include the effects of water-releases, evaporation etc., and rain water supplies). When the exchange coefficients of the spillways are set on 1 the salt concentrations of the lakes reduce (Test case 3A), when the coefficients are set on 0 (no salt outflow, Test case 3B) the concentration fluctuates in dependence of the volume of the lakes.

Conclusions Test series B:

From the test runs with initial salt concentration of Gatun Lake and Miraflores Lake set on 30 ppt and salt concentration in other basins set on zero, we conclude:

Salt from Gatun Lake and Miraflores Lake migrates properly to all lower basins; water releases through Gatun Dam and Miraflores Dam cause a decrease of salt concentration in Gatun Lake and Miraflores Lake (as required); time-dependent exchange of salt between forebays / tailbays and lakes functions correct; exchange of (salt) water between basins in steps I and II of ship movements functions correct; transfer of ship-bound water volumes between basins functions correct; water movements and salt transfer related to turn arounds are correct simulated, water levels and water volumes in lakes remain as monthly prescribed.

Test series C

The last series of tests was focused on the process of salt intrusion from Pacific and Atlantic Ocean. In the simulation runs the salt concentration in the tailbays at the Pacific and Atlantic side was set on a constant value of 30 ppt, while the initial concentration in all other basins was set on zero. Next test cases were executed:

Test case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
7A	c1	d1	Jan 1 – Jan 31, 2002	scenario	salt intrusion
7B	c1	d2	Jan 1 – Jan 31, 2002	scenario	salt intrusion
7B-R	c1	d6	Jan 1 – Jan 31, 2002	scenario	salt intrusion
7C	c11	d1	Jan 1 – Jan 31, 2002	scenario	salt intrusion
7C-R	c11	d5	Jan 1 – Jan 31, 2002	scenario	salt intrusion
7D	c12	d1	Jan 1 – Jan 31, 2002	scenario	salt intrusion
7E	c11	d2	Jan 1 – Jan 31, 2002	scenario	salt intrusion
7E-R	c11	d6	Jan 1 – Jan 31, 2002	scenario	salt intrusion

Table 6.14 Test cases series C: salt concentrations in Pacific and Atlantic tailbays are constant 30 ppt, initial concentrations of all other basins zero

As an example, some results of Test case 7E (single ship movement from Pacific to Atlantic Ocean each day, ship volume S = 90,000 m^3) are presented in Figures TC7E-1 and TC7E-2. In the similar Test case 7E-R the ship moves from Atlantic to Pacific Ocean; results are shown in Figures TC7ER-1 and TC7ER-2. The figures present the salt concentration of the locks at both sides of the canal as a function of time. Though the exchange coefficients used in these simulations are not correct, the figures demonstrate that the direction of the ship is important: more salt water is transferred in upward direction in the case of downlockage than in the case of uplockage. As can be seen the salt concentration in the lower locks raises even above the salt concentration in the seaside tailbays, when exchange coefficients are not well chosen.

Conclusions Test series Cs:

From the test runs with initial salt concentration of both seaside tailbays set on 30 ppt, and salt concentration in other basins set on zero, we conclude:

Salt from seaside tailbays migrates to higher basins; time dependent exchange of salt between forebays / tailbays and lakes functions correct; exchange of (salt) water between basins in steps I and II of ship movements functions correct; transfer of ship-bound water volumes between basins functions correct; water levels and water volumes in lakes remain as prescribed.

6.5 Validation of simulation model

The simulation model is validated on the basis of the salinity measurements in wet and dry season. Volume averaged salinity values found in the lakes were used for calibration of the model (Gatun Lake: volume-averaged salt concentration c < 0.1 ppt, Miraflores Lake: volume-averaged salt concentration c = about 0.7 ppt in the wet season and up to about 1.5 ppt in the dry season). The approximate range of volume averaged salinity values of other basins of the canal system, shown in Table 3.4, was also taken into account.

Input data were chosen as decribed in Section 6.1. The standard day pattern with ship-movements scenarios, turn-around scenarios and water-release scenarios as described in Section 6.2 was selected for validation. Many cases were built up with variable duration. In these cases the exchange coefficients (see also Section 6.3) were such tuned that the salt concentration of Miraflores Lake and Gatun Lake was correctly predicted. In particular the selection of the exchange coefficients used in the water-release scenarios was of importance.

6.5.1 Exchange coefficients water releases

In final valdation runs we have applied an exchange coefficient $e_x = 1.5$ for both Miraflores Spillway and the cooling water offtake beside Miraflores Dam. Salt water that intrudes through the locks into the relatively small Miraflores Lake, is rather well distributed over the full lake volume, but the salt concentration in the southern area tends to be higher (as was found with the salinity measurements). Also because of possible short-cut flows between Miraflores Locks and the spillway / cooling water offtake the spilled water will most probably have a somewhat higher salt concentration than the water of the lake (volume-averaged). This is reflected in the choice of $e_x = 1.5$. The application of this exchange coefficient in the simulation model together with the selected set of exchange coefficients for both the Pacific and Atlantic locks yielded a full reproduction of the season-dependent salinity levels of Miraflores Lake.

The choice of the exchange coefficient for water releases at Gatun Dam is more difficult, since salt concentrations in Gatun Lake are small and therefore not well-known (salt concentrations are certainly smaller than about 0.1 ppt, which was the lower limit of the CTD sensors used during our site surveys). Yet, from our measurements we know that salt water enters Gatun Lake, in particular at the end of a series of downlocking ships.
For Gatun Lake with a factor 220 greater volume than Miraflores Lake, the assumption that the intruded salt water is diluted over the full lake volume, is not plausible, seen also the large quantities of water which are spilled through the locks and the spillway / hydropower station (the total drained / spilled water quantity in an average year amounts to about 85% of the mean water volume of the lake, see Section 5.5). These outflows force the water in the lake to flow in the northern direction and in Gaillard Cut in southern direction. It means that the salt water that has intruded the lake through Gatun Locks, remains most probably in the northern area of the lake; consequently, the water released at Gatun Dam has a higher salt concentration than the water of the full lake (volume-averaged). We expect that the intruded salt water follows a path along the bed of the deeper shipping channel and continues along the deeper parts (possibly also the bed of the former Chagres River) to the area near Gatun Dam. The quantity of salt water that intrudes Gatun Lake through Pedro Miguel locks is smaller, as is demonstrated with the simulations (see hereafter), and plays a lesser role.

An exchange coefficient $e_x = 7.5$ was used in final validation runs for water releases at Gatun Spillway and Gatun Power Station, together with the selected set of exchange coefficients for both the Pacific and Atlantic locks. With the exchange coefficient $e_x = 7.5$ the salt concentration of the released water is 7.5 times as high as the volume-averaged salt concentration of Gatun Lake. Prior to this choice we have varied this exchange coefficient: several values between 1 and 100 were used in simulations to check the effect on the salinty levels. We found the following results:

Exchange coefficient e_x	*Volume-averaged salt concentration Gatun Lake (ppt)*		*Salt concentration near Gatun Dam*	
	wet season	*dry season*	*wet season*	*dry season*
1.0	0.045	0.080	0.045	0.080
2.5	0.030	0.040	0.075	0.100
7.5	0.010	0.027	0.075	0.203
15.0	0.005	0.021	0.075	0.315
100.0	0.001	0.012	0.100	1.200

Table 6.15 Effect of exchange coefficient Gatun Spillway and Gatun Power station on salt concentration levels Gatun Lake

It appears that the volume-averaged salt concentration of Gatun Lake decreases in a non-lineair way with an increase of the exchange coefficient. Simultaneously, however, the salt concentration near Gatun Dam increases. In reality a salt concentration greater than 0.2 ppt near Gatun Dam is not plausible, since we did not measure such high values. This excludes a choice for an exchange coefficient $e_x > 7.5$. Smaller values for the exchange coefficient e_x lead to a relatively high salt concentration level in the lake, which seems not to correspond with the real concentration level. For those reasons we have selected an exchange coefficient $e_x = 7.5$.

6.5.2 Results of validation runs

The results of final validation runs for a period of 1 year and 10 years are shown as a function of time in Figures VAL1-1 through VAL1-9, and VAL10-1 through VAL10-2 respectively. Values are printed at the end of each day, after turn arounds which prepare the locks for uplockage scenarios the next day. This means that water levels in Locks A-west and A-east are low, and that water levels in Locks B-west and B-east are equal to the water level of Miraflores Lake, similar as the water levels in Locks C-west and C-east. The water levels in Locks D-west and D-east are low, while water levels in Locks E-west, E-east, F-west and F-east are high, the latter equal to the water level of Gatun Lake.

As is shown in Figures VAL1-1 through VAL1-9 (simulation for period of 1 year) salt concentrations in the locks vary with the tidal movements in the seaside tailbays, in particular at the Pacific side. The effect of the tide is also visible in Figure VAL1-9, which shows the salt concentration of Miraflores Lake. Salt concentrations of the locks and lakes adapt to the monthly water level changes of Gatun Lake. Volume-averaged salt concentrations of the lakes rise from the initial zero level to a maximum and subsequently decrease in the wet season to a minimum as a result of the greater water spillages and smaller salt concentrations in the seaside tailbays (Figures VAL1-8 and VAL1-9). The relatively small fluctuations caused by tidal variations are in the long run of minor importance.

From Figures VAL1-5 and VAL1-7 it appears also that salt concentration values of the upper locks at the Atlantic side (upper Gatun Locks: locks F-west and F-east) are higher than those at the Pacific side (Pedro Miguel Locks: locks C-west and C-east), even with high water in the upper Gatun Locks and low water in the Pedro Miguel Locks. 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 form the 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 certain minimum value. 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.

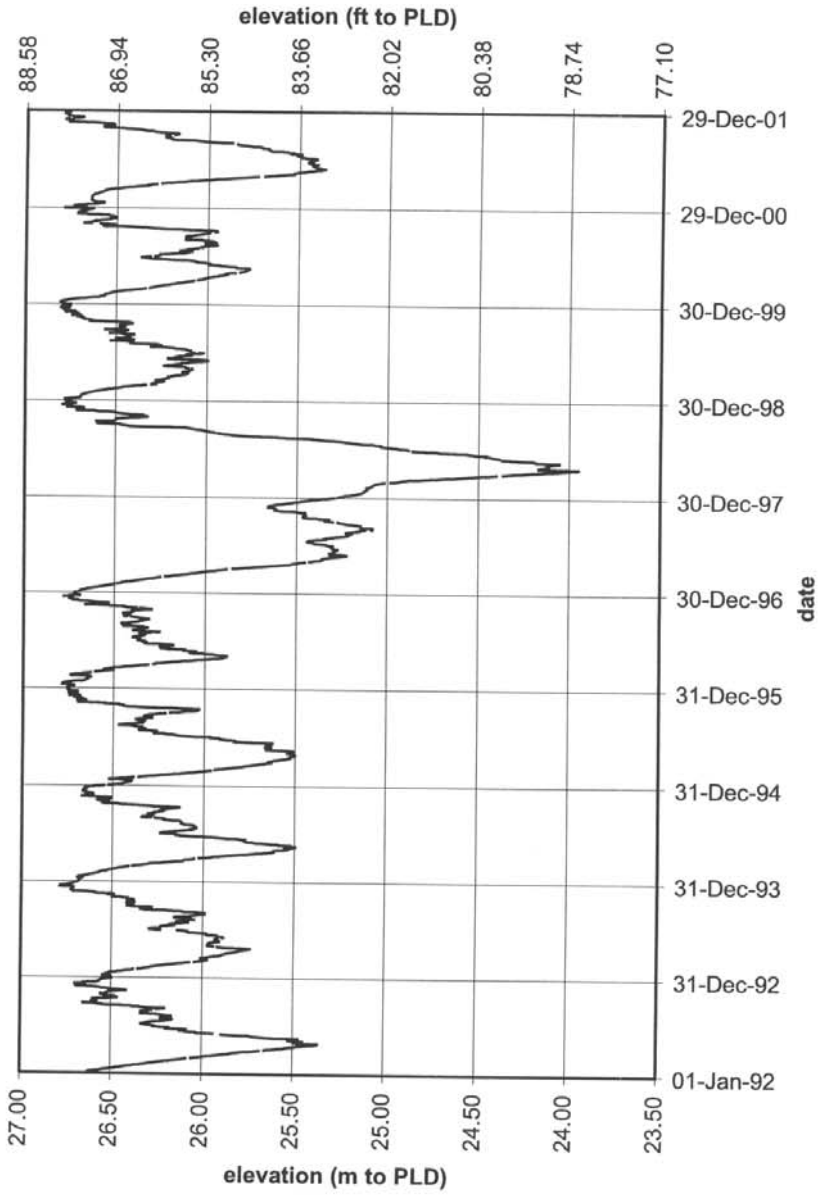
The development of the volume-averaged salt concentration of Miraflores Lake and Gatun Lake during a period of 10 years is shown in Figures VAL10-1 and VAL10-2. The salt concentration fluctuates in dependence of wet and dry season. The effect of tidal fluctuations in the seaside tailbays is dampened out in these long-duration simulations. Salt concentrations in the lakes become already stable after a period of 2 years.

6.5.3 Conclusions of validation runs

The main conclusions of the validation runs are:

- With the selected exchange coefficients the simulation model is able to reliably predict the levels and seasonal variations of the salt concentration of Miraflores Lake and Gatun Lake.
- The volume-averaged salt concentration of Miraflores Lake varies between 0.7 – 1.5 ppt in dependence of seasonal influences: (i) variation of salt concentration and temperature of the water in the Pacific tailbays, (ii) lesser water releases in the dry season. The salt concentration of Gatun Lake varies similarly, mainly because of the lesser water releases in the dry season. The volume-averaged salt concentration of Gatun Lake is small and remains below 0.03 ppt, far below the fresh-water limit value of about 0.45 ppt salinity. (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)). Local salt concentrations in the lakes can be higher than the computed volume-averaged salt concentrations.
- The large tidal variation at the Pacific side causes a relatively small variation of the salt concentration in Miraflores Lake in particular, but is in the long run not of importance for the salt concentration level in the lakes.
- At present more salt intrudes Gatun Lake through Gatun Locks than through Pedro Miguel Locks and Gaillard Cut.
- Under the present meteorological and hydrological conditions, with the present ship-transit intensities and ship dimensions, and with the present water management of Gatun Lake and Miraflores Lake, stable salt concentrations in the lakes are obtained after a period of only 2 years (starting from zero salinity in the lakes).

Figures

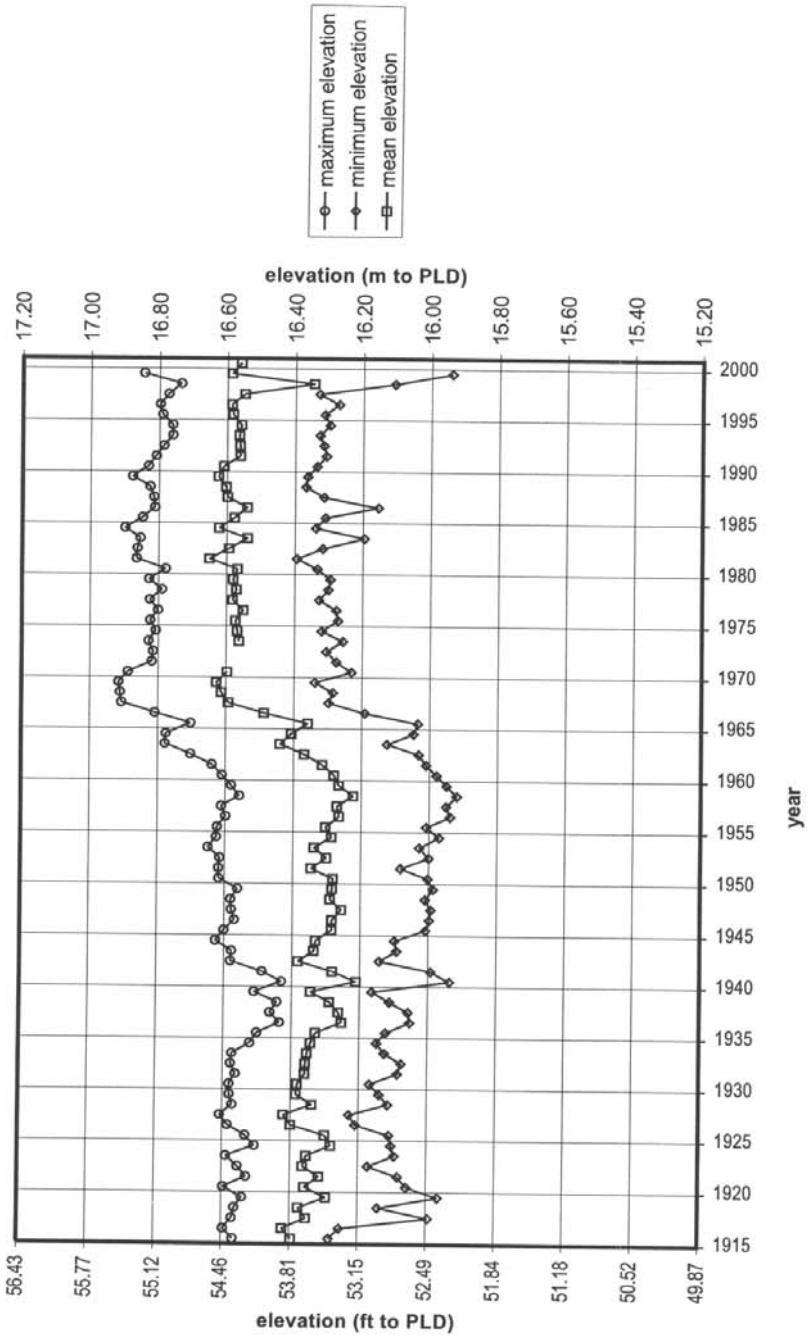


GATUN LAKE
WATER LEVEL VARIATION IN PERIOD 1992 - 2001

WL | DELFT HYDRAULICS

Q 3039

Fig. 2 .1

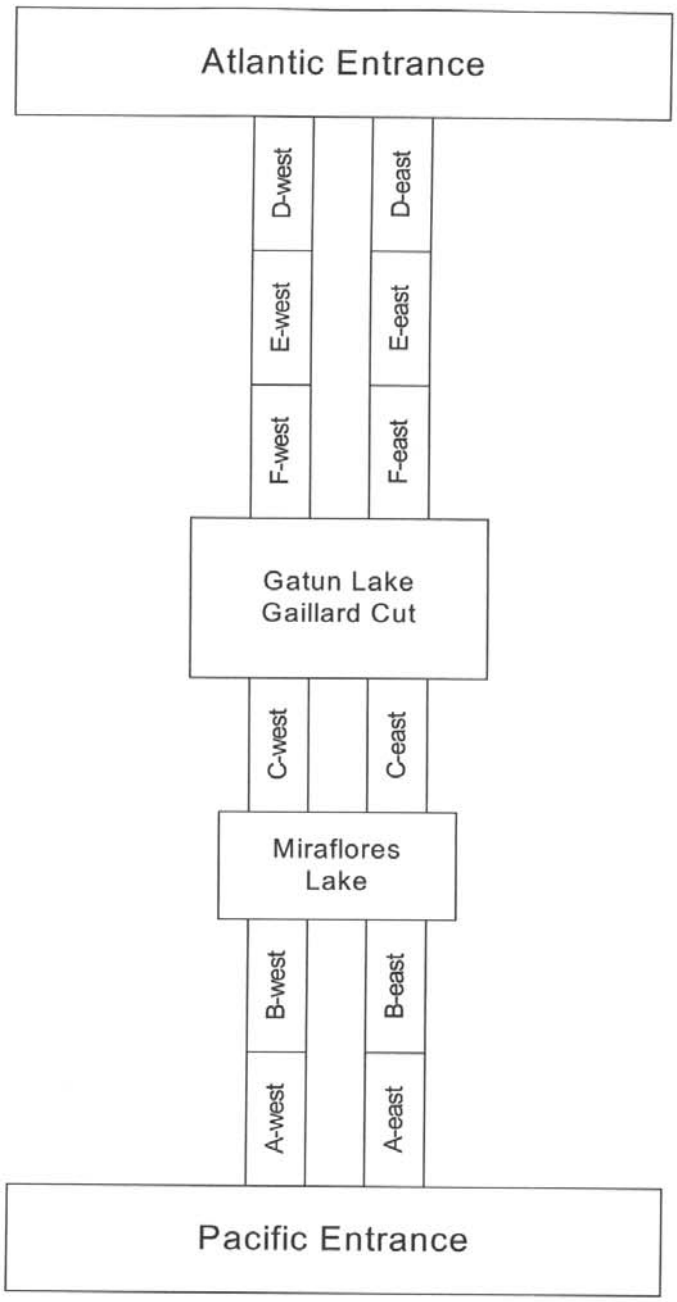


MIRAFLORES LAKE
AVERAGED MEAN, MAX. AND MIN. WATER LEVEL

WL | DELFT HYDRAULICS

Q 3039

Fig. 2.2

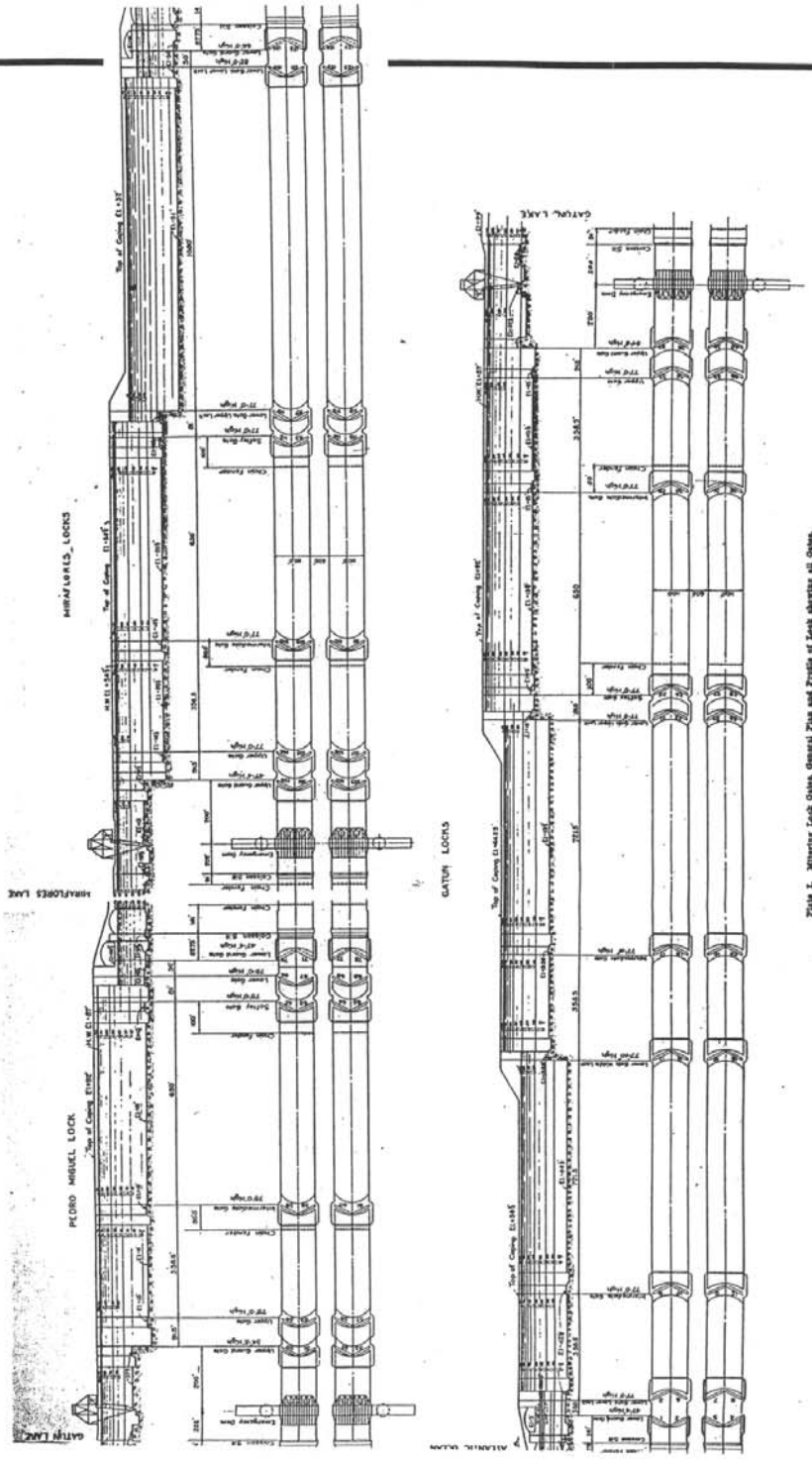


LOCK IDENTIFICATION

WL | DELFT HYDRAULICS

Q 3039

Fig. 2.3

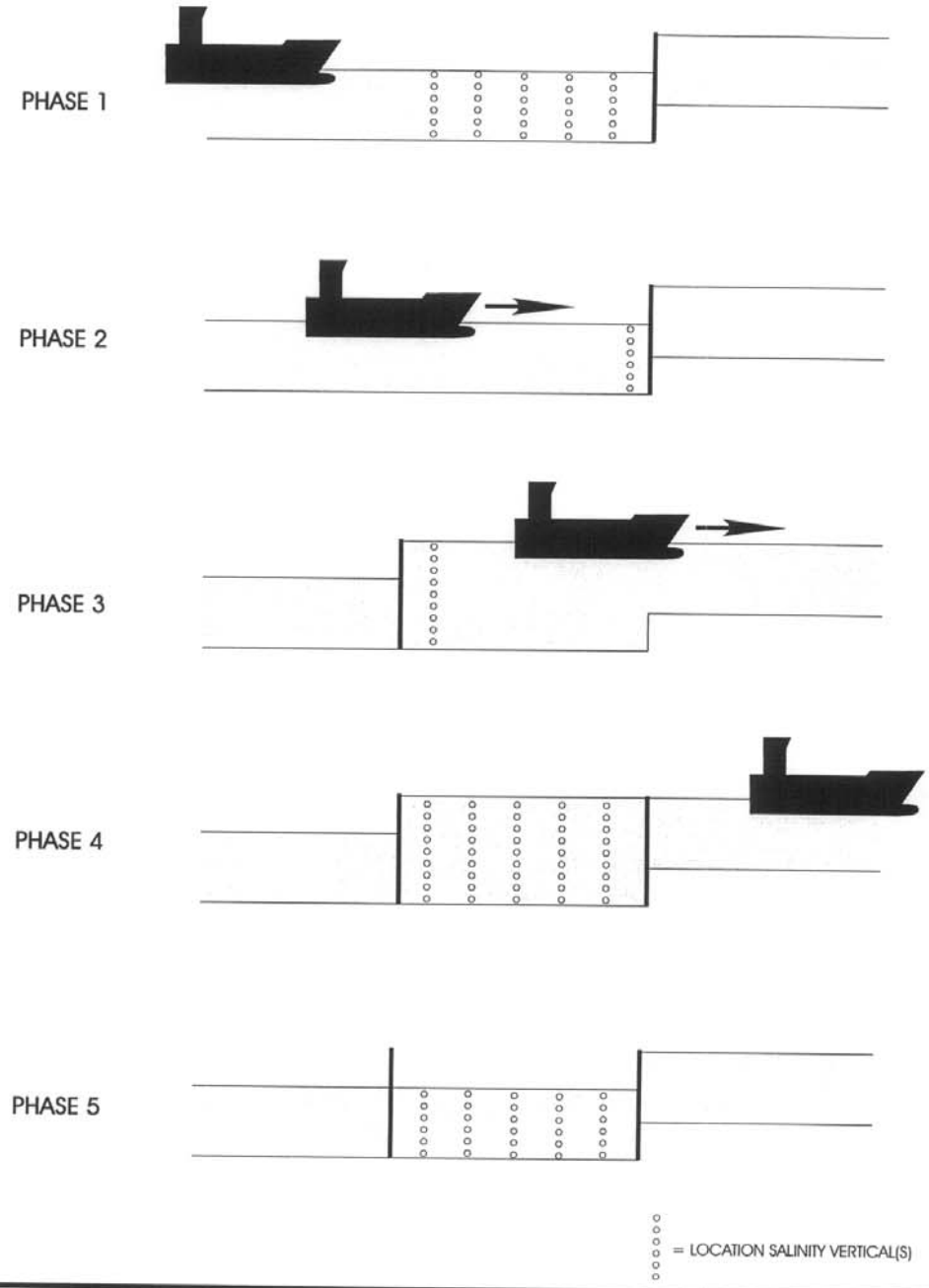


PLAN AND SECTION OF LOCKS ON THE PANAMA CANAL

WL | DELFT HYDRAULICS

Q 3039

Fig. 2.4

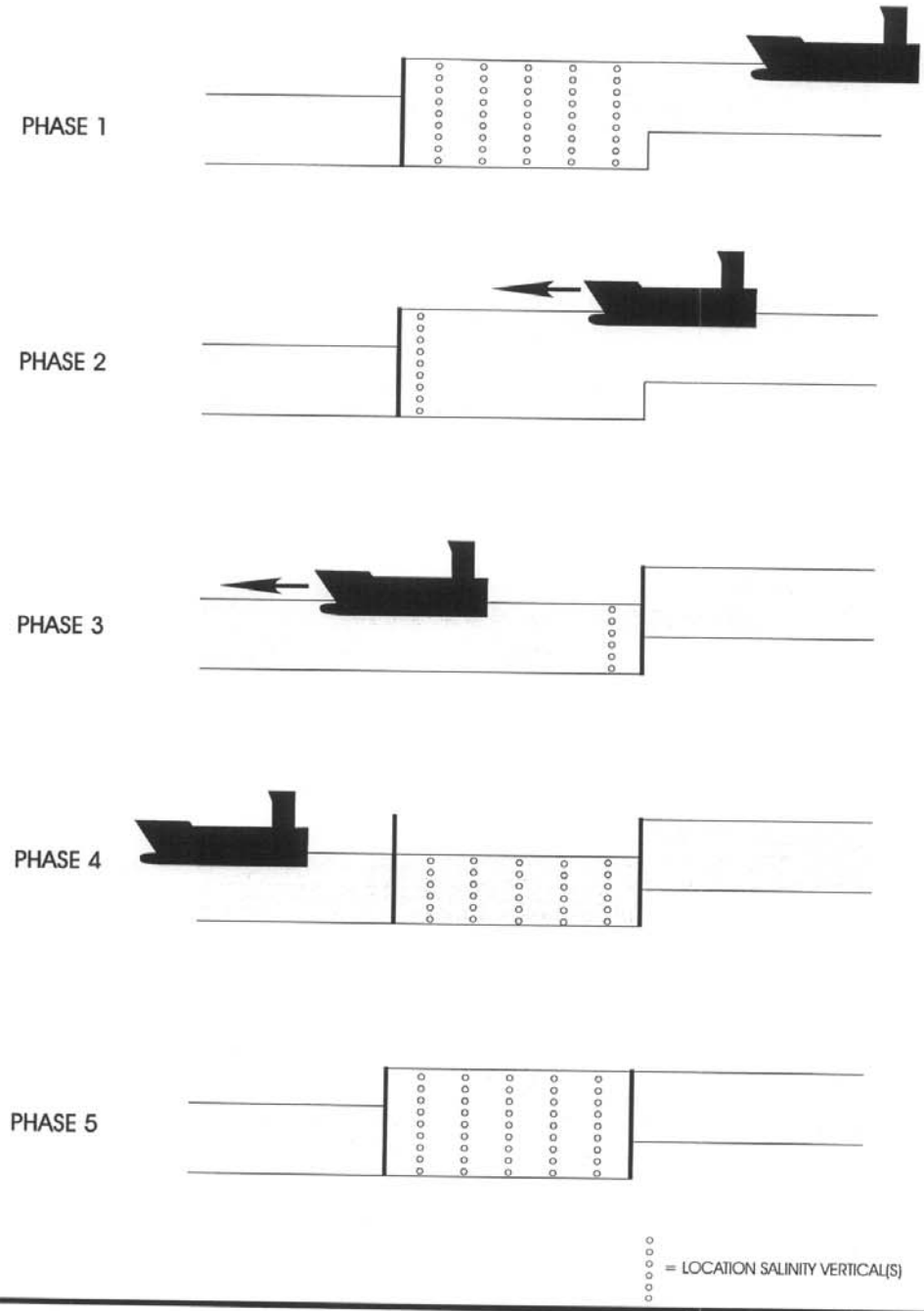


UPLOCKAGE
MEASUREMENT PHASES LOCKS

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.1

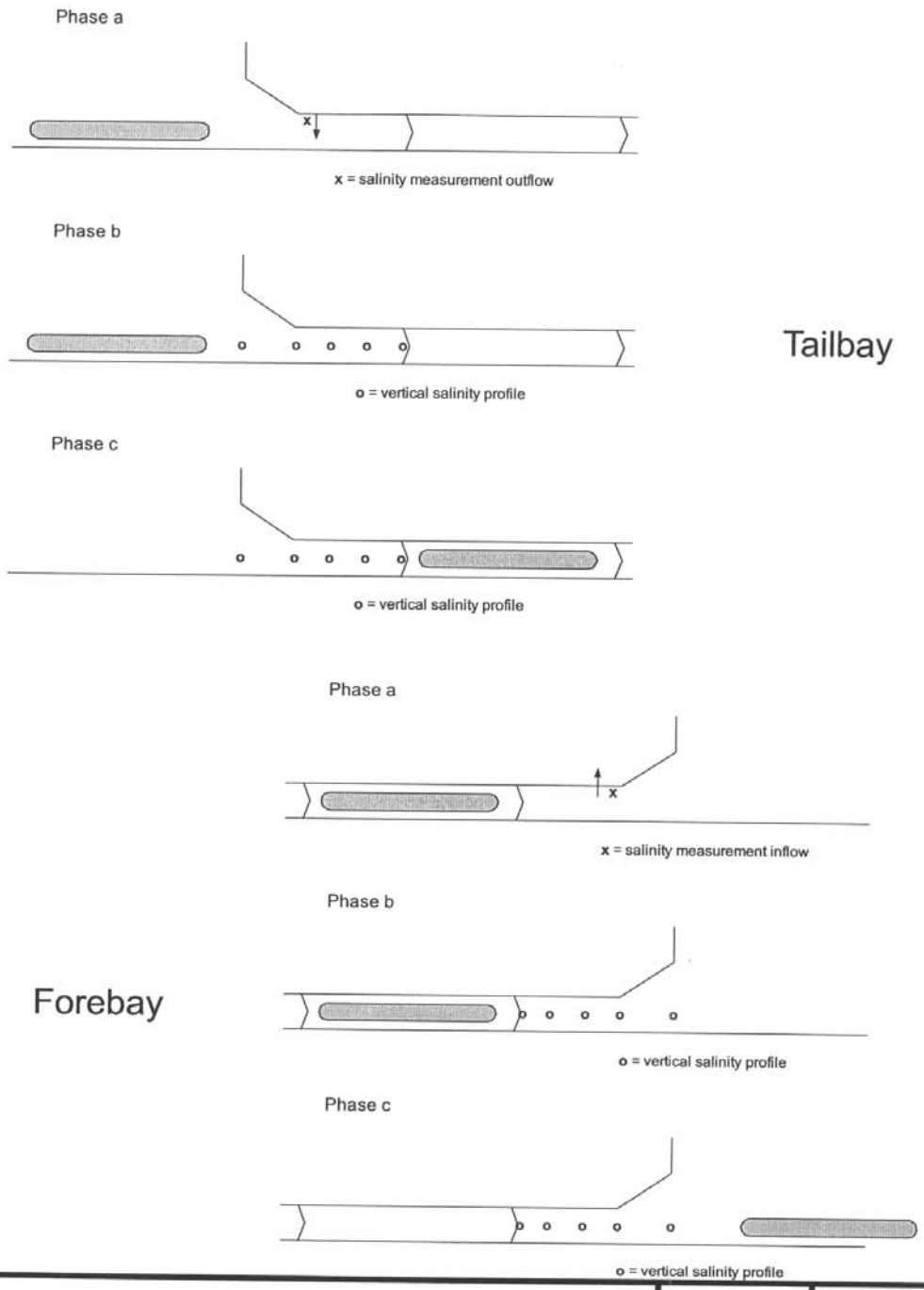


DOWNLOCKAGE
MEASUREMENT PHASES LOCKS

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.2

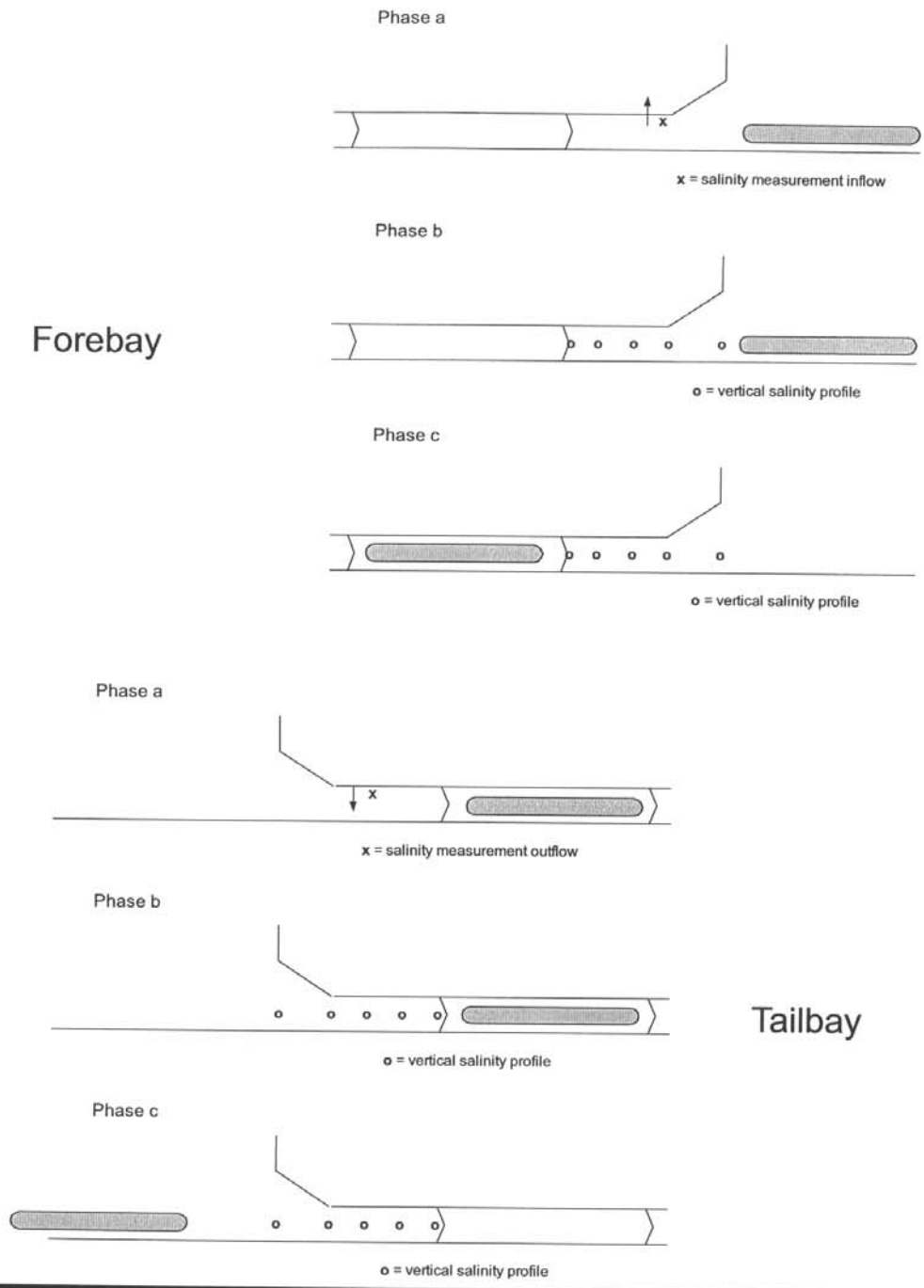


UPLOCKAGE
MEASUREMENT PHASES TAILBAY / FOREBAY

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.3

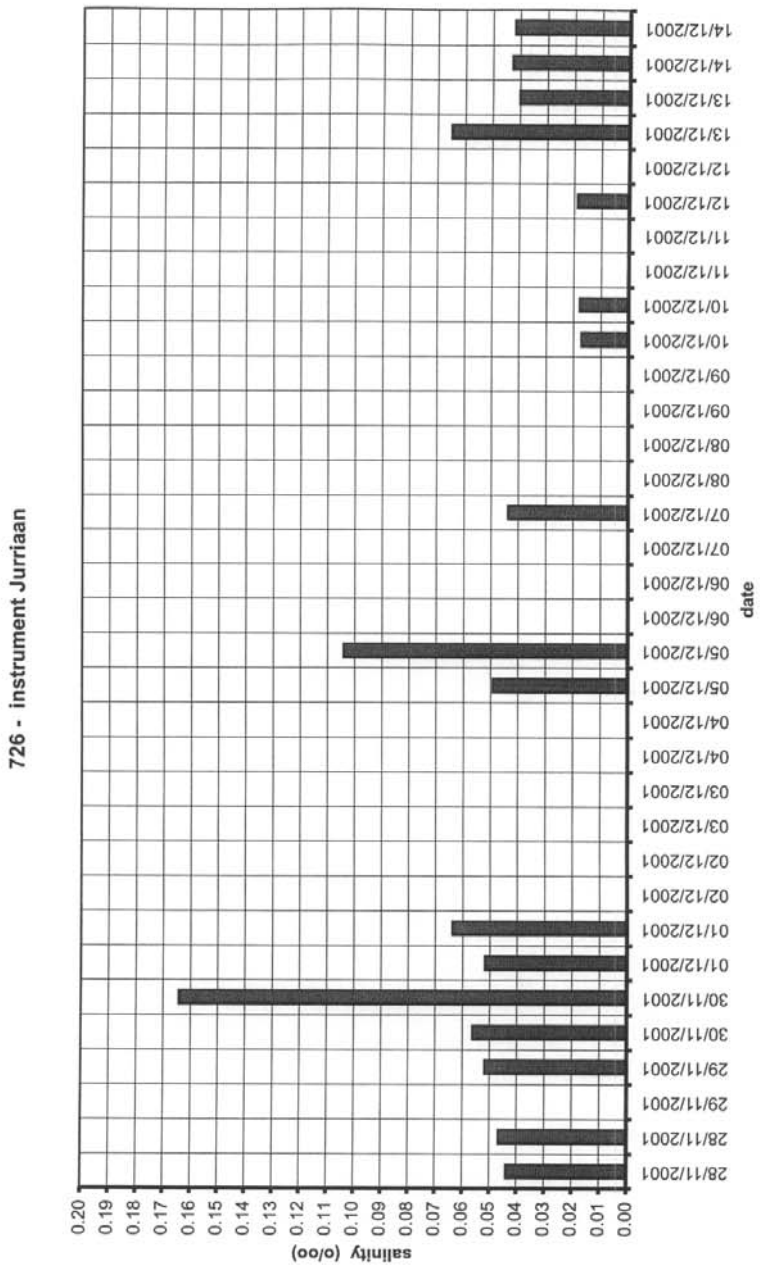


DOWNLOCKAGE
MEASUREMENT PHASES FOREBAY / TAILBAY

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.4

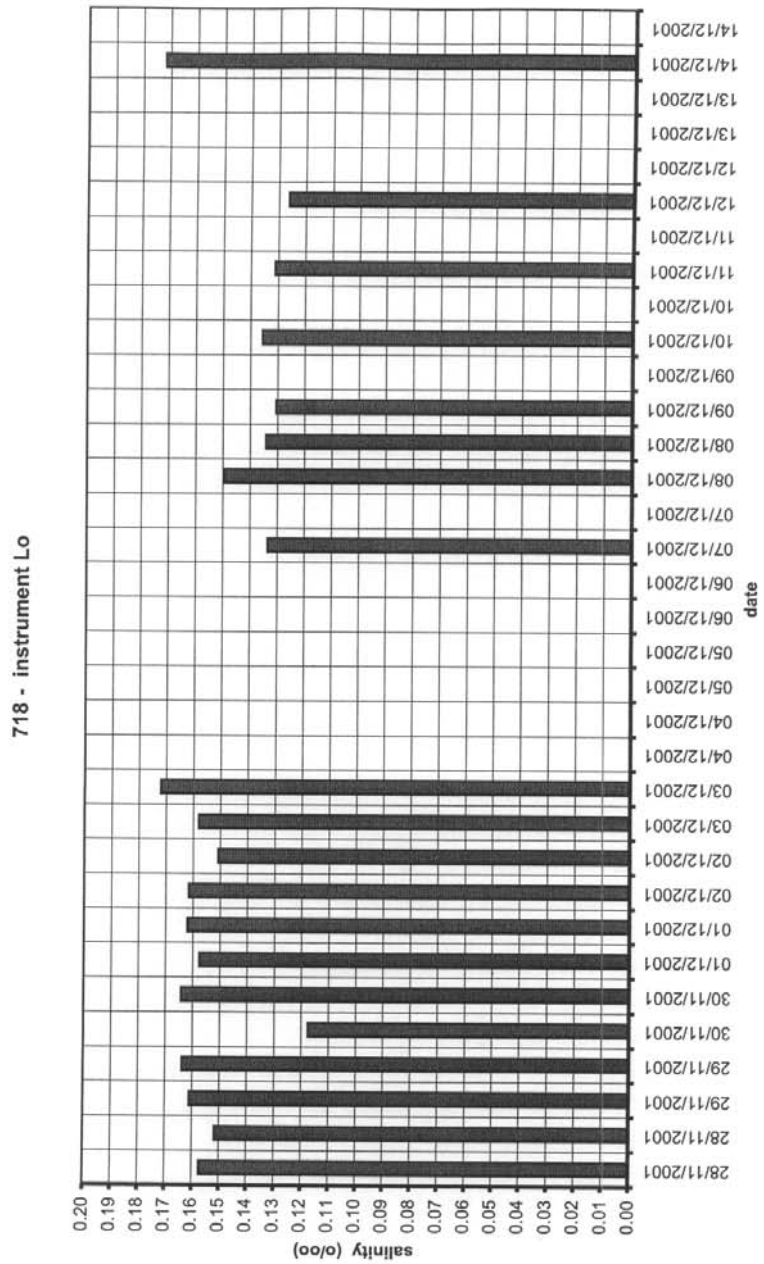


WET SEASON
ZERO MEASUREMENTS INSTRUMENT 726

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.5

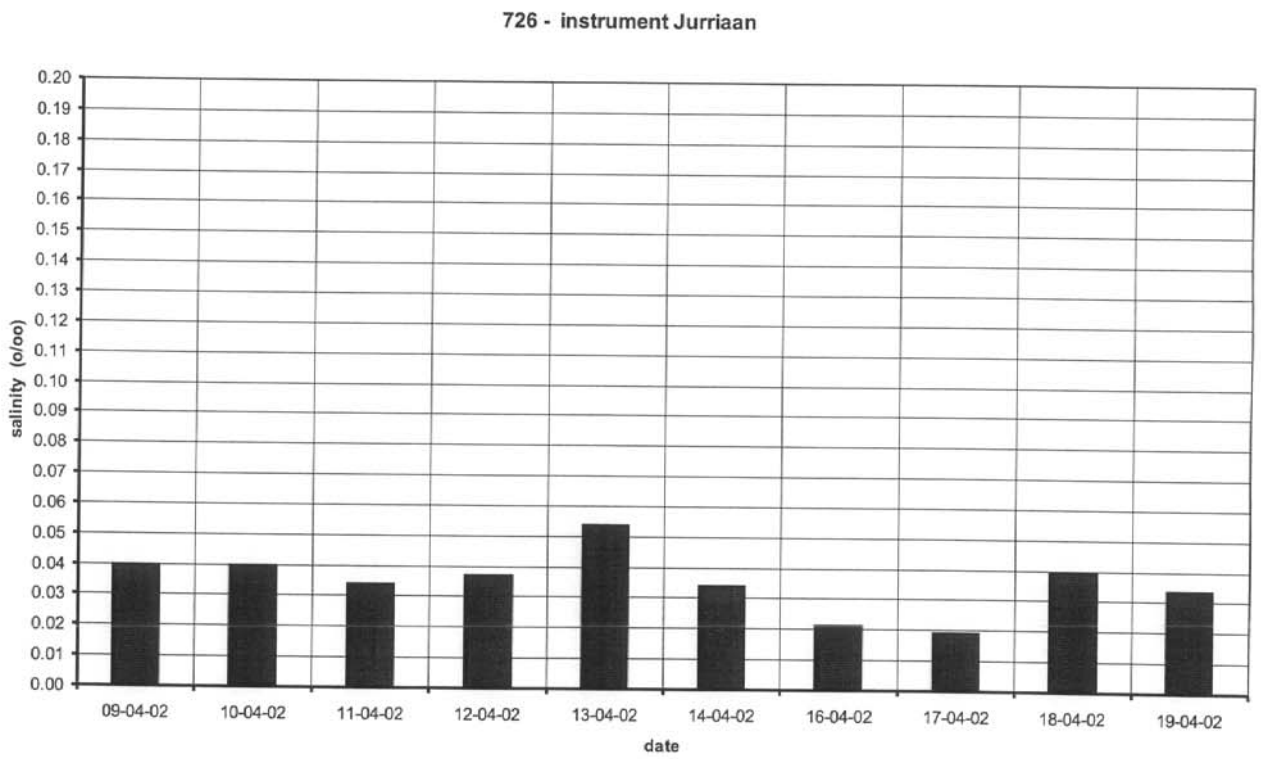


WET SEASON
ZERO MEASUREMENTS INSTRUMENT 718

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.6

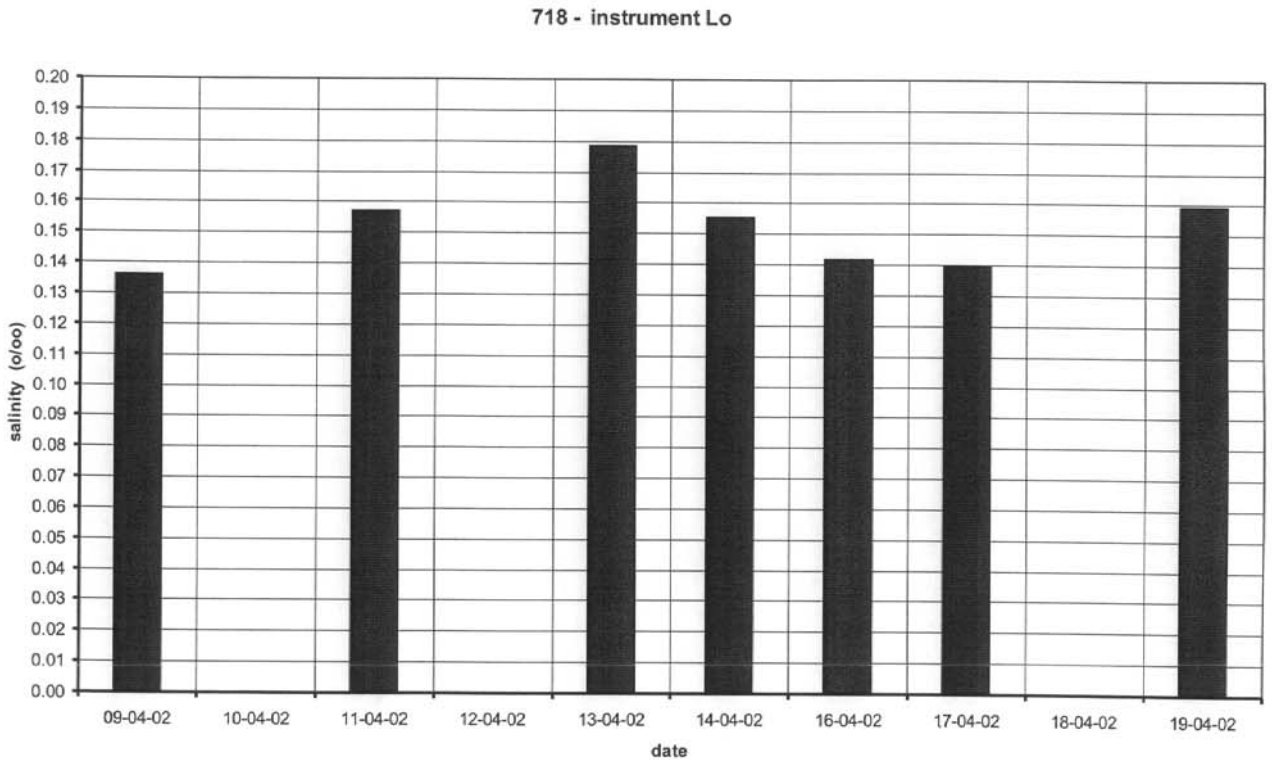


DRY SEASON
ZERO MEASUREMENTS INSTRUMENT 726

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.7

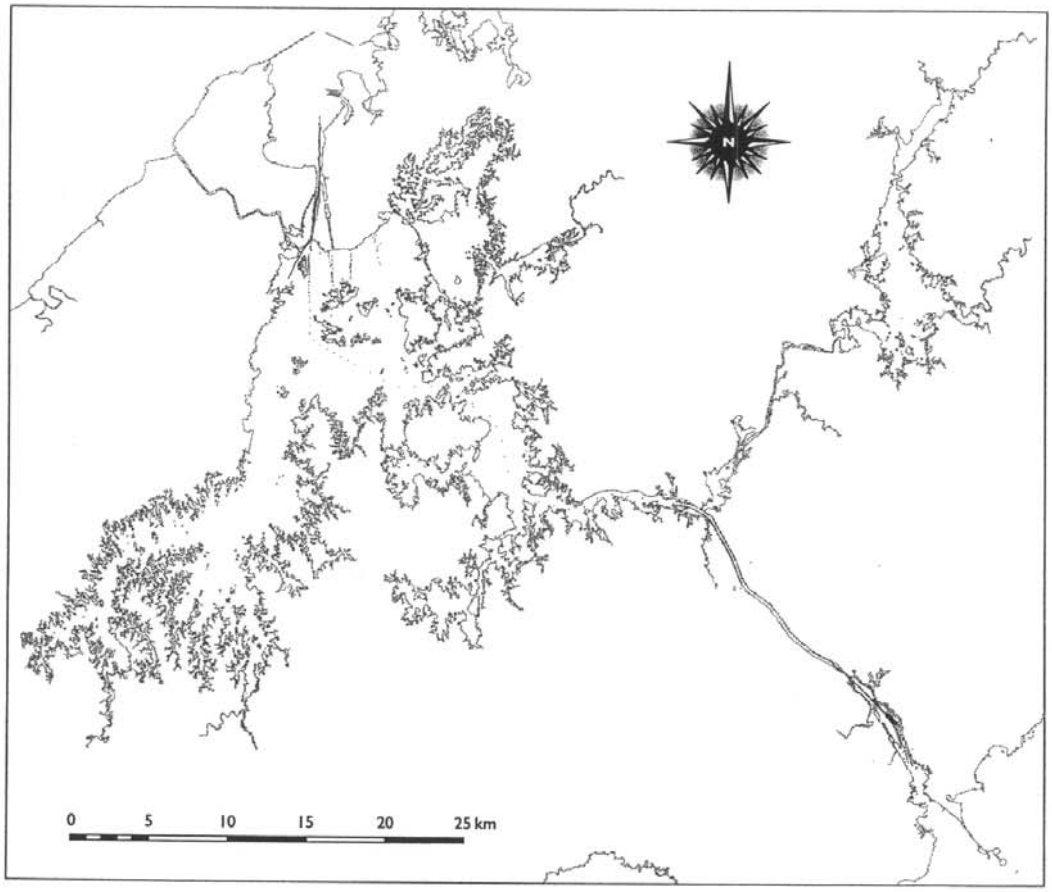


DRY SEASON
ZERO MEASUREMENTS INSTRUMENT 718

WL | DELFT HYDRAULICS

Q 3039

Fig. 3.8

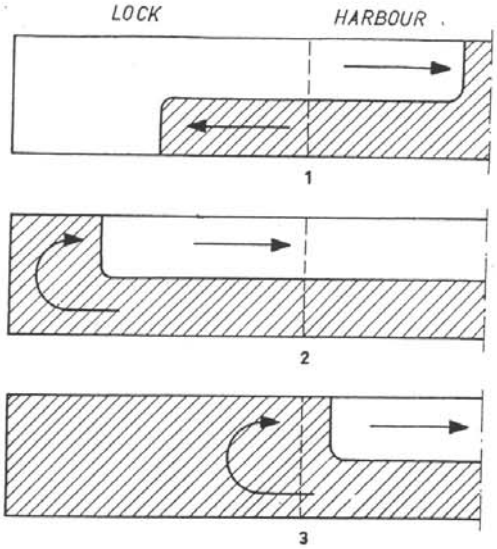


WET SEASON
LOCATION OF MEASUREMENTS

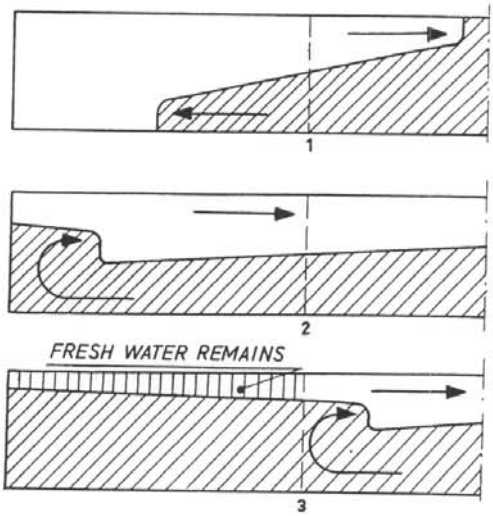
WL | DELFT HYDRAULICS

Q 3039

Fig. 3.9

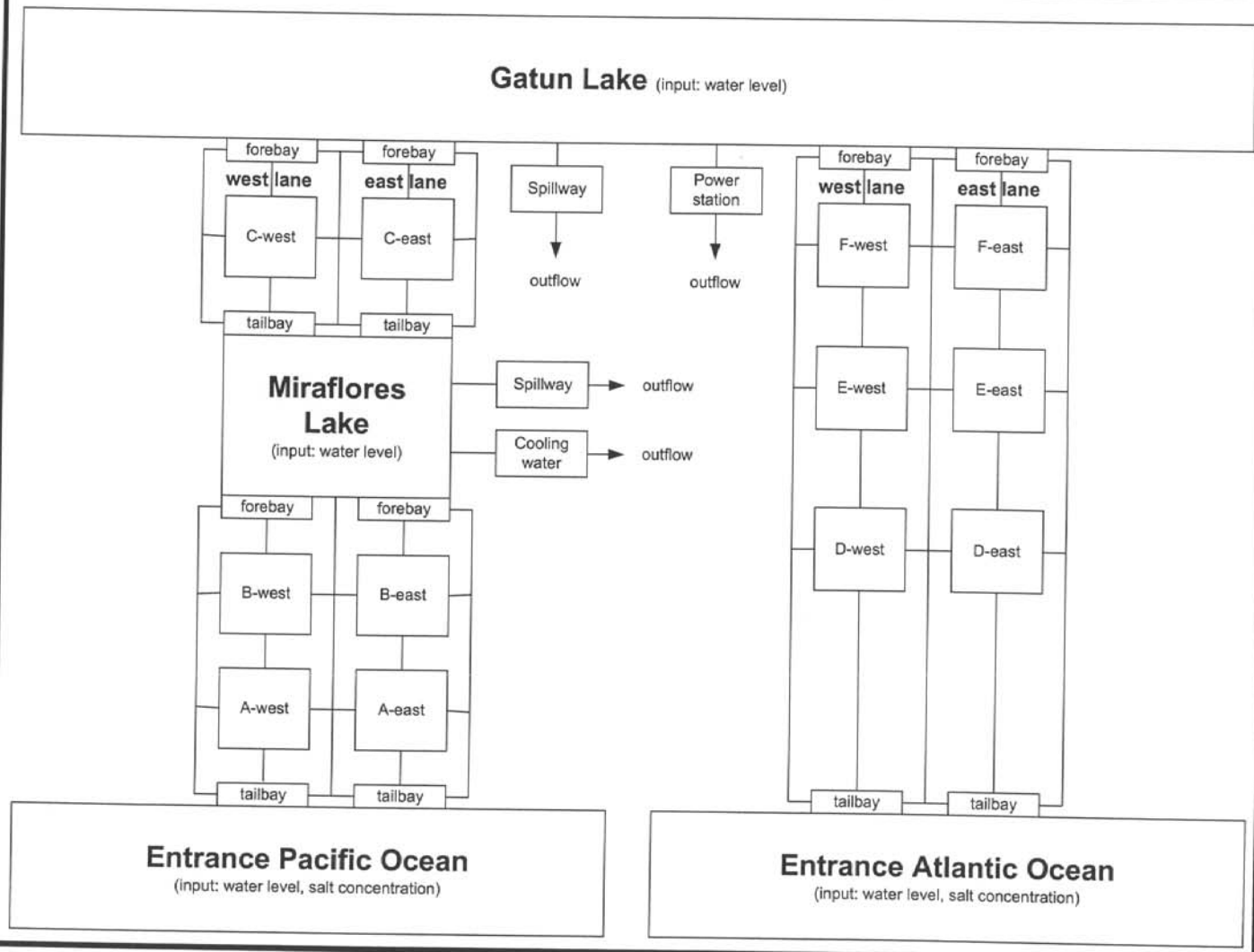


A. IDEALISED FORM



B REAL FORM
(SIMPLIFIED)

LOCK EXCHANGE PROCESSES		
WL | DELFT HYDRAULICS	Q 3039	Fig. 3.10

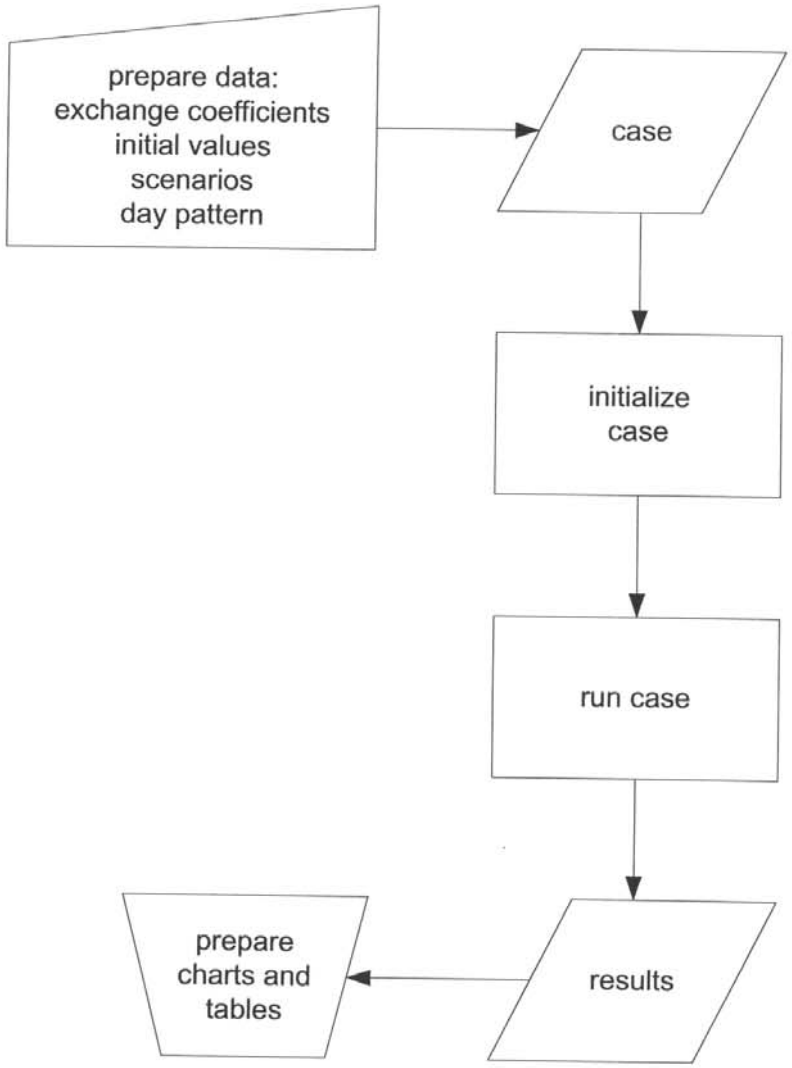


SIMULATION MODEL
NODES AND HYDRAULIC CONNECTIONS

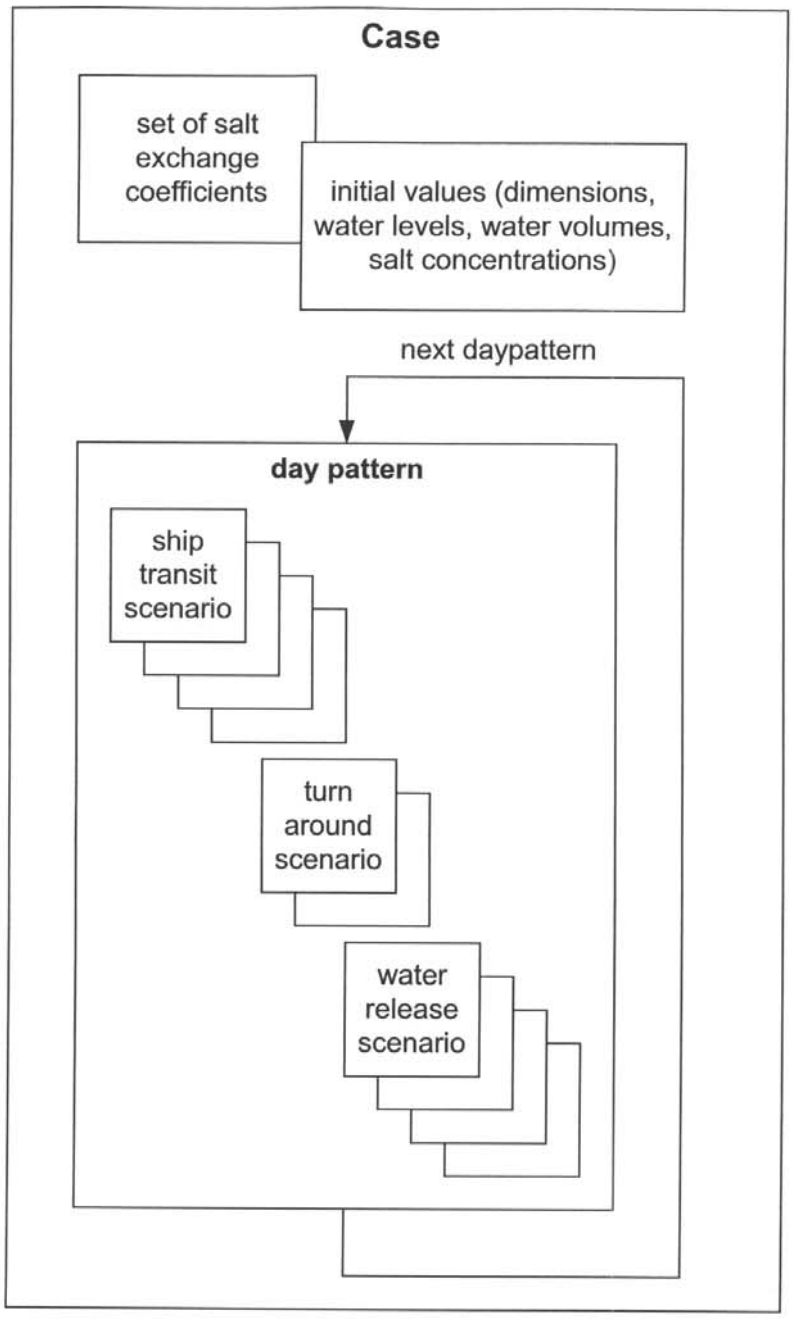
WL | DELFT HYDRAULICS

Q 3039

Fig. 5.1



SIMULATION MODEL FLOW CHART		
WL | DELFT HYDRAULICS	Q 3039	Fig. 5.2

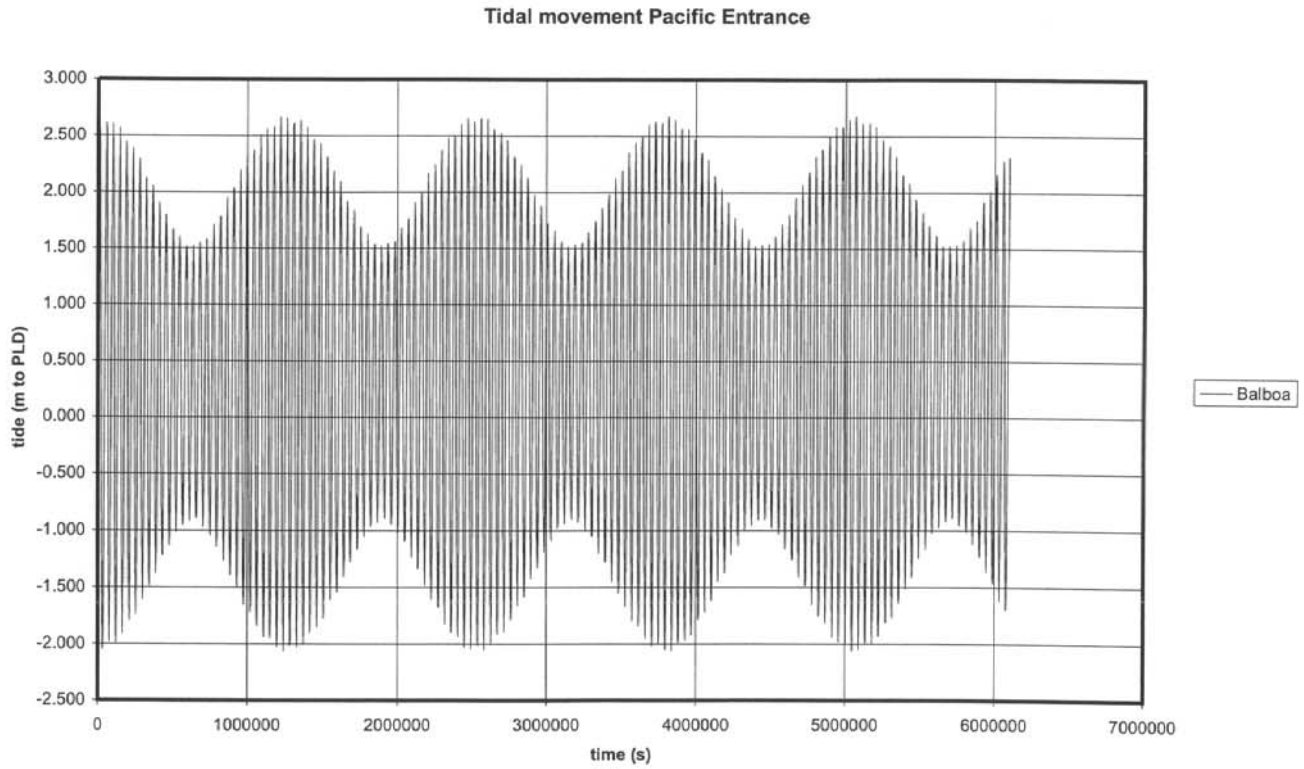


SIMULATION MODEL
COMPOSITION OF CASE

WL | DELFT HYDRAULICS

Q 3039

Fig. 5.3

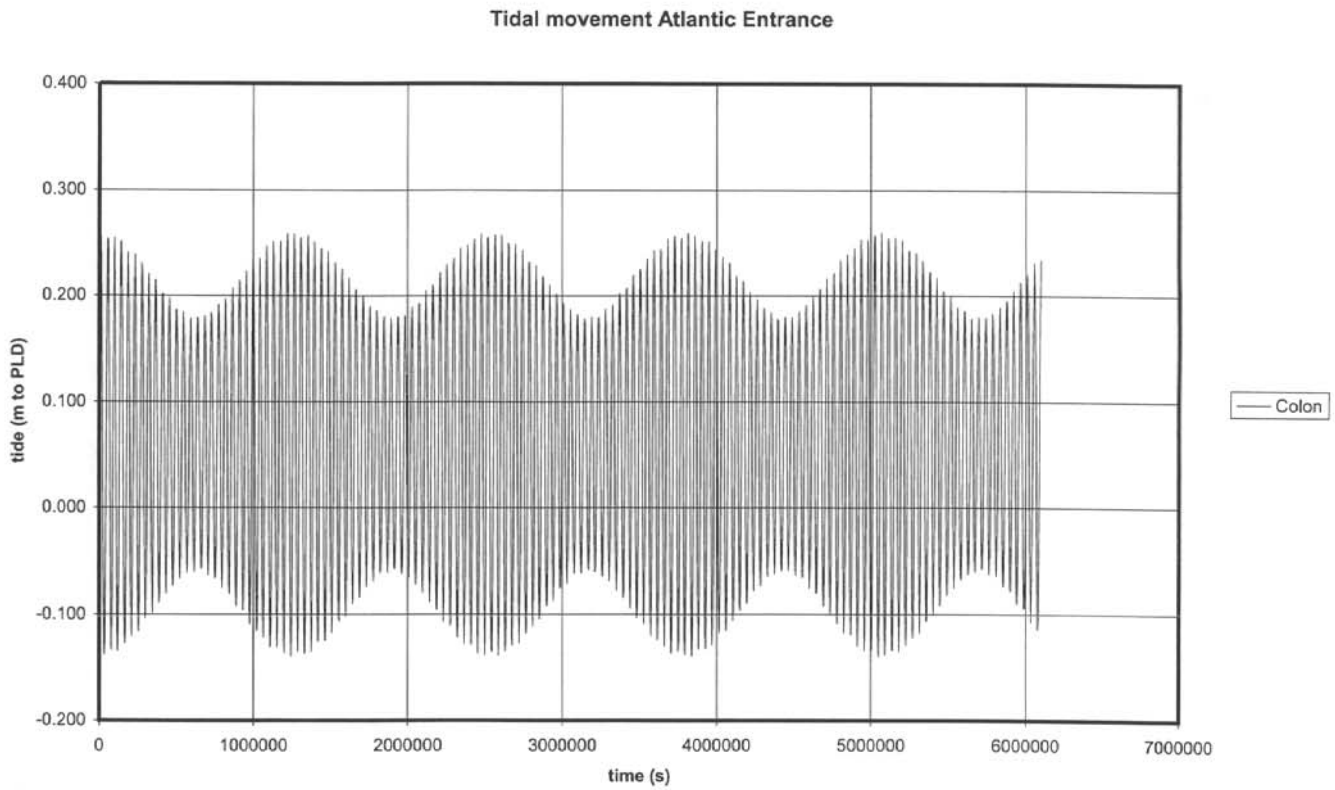


TAILBAY MIRAFLORES LOCKS
PREDICTION OF TIDAL MOVEMENT

WL | DELFT HYDRAULICS

Q 3039

Fig. 5.4

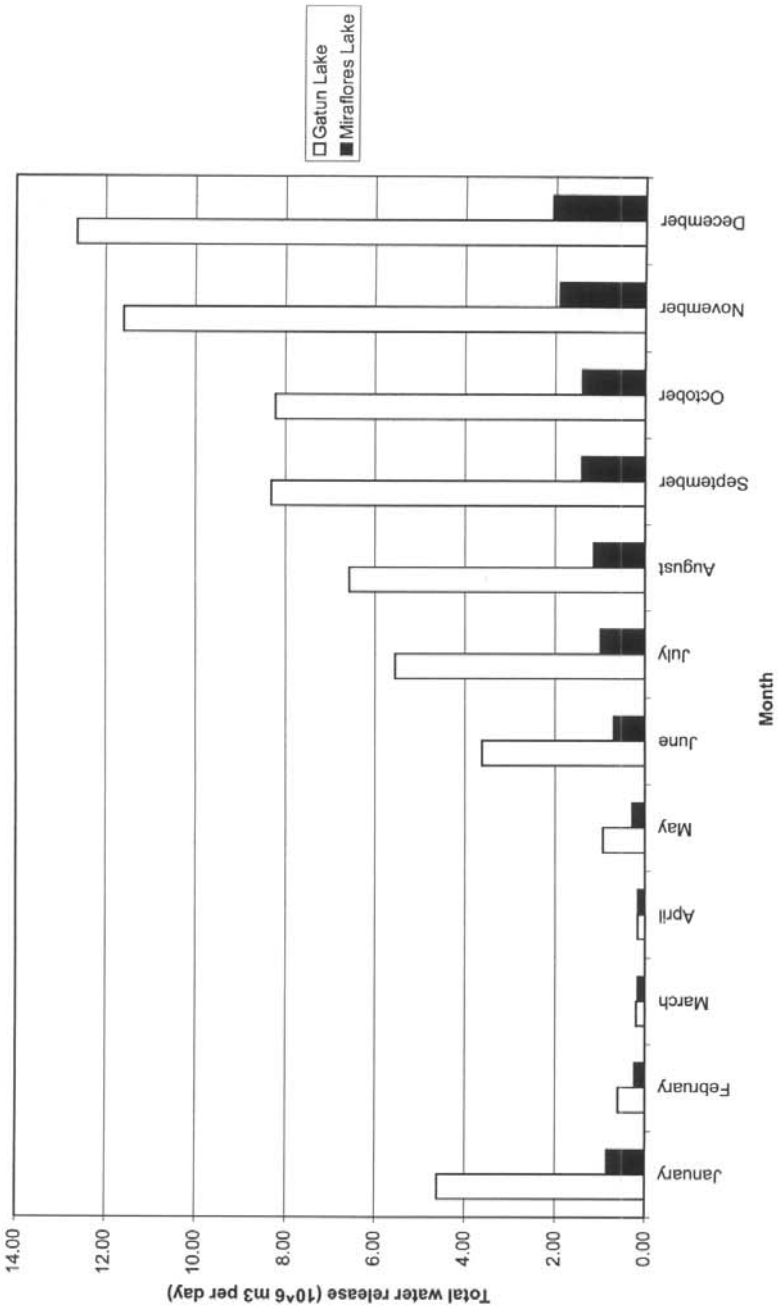


TAILBAY GATUN LOCKS
PREDICTION OF TIDAL MOVEMENT

WL | DELFT HYDRAULICS

Q 3039

Fig. 5.5



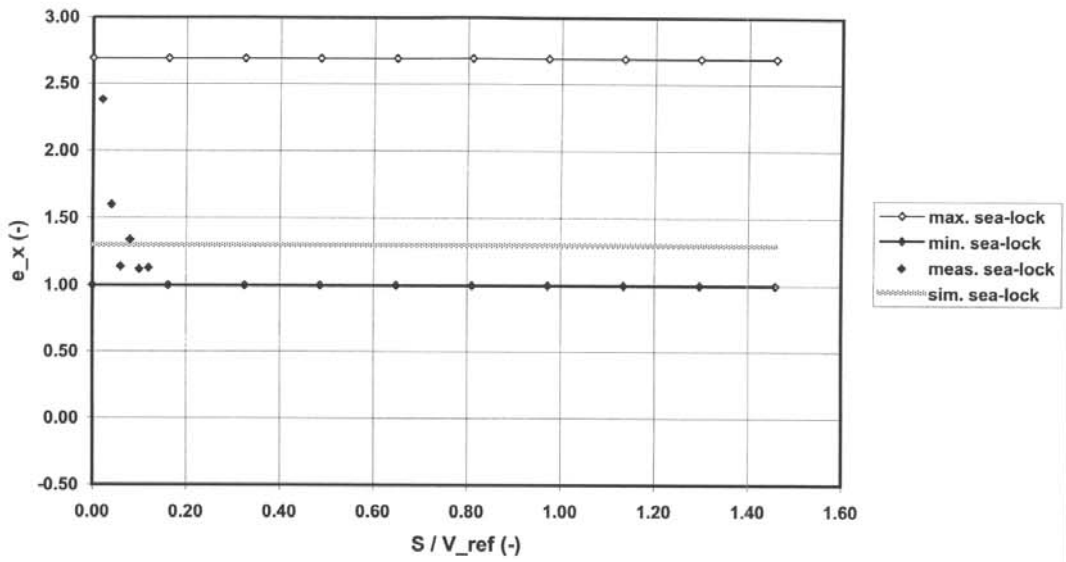
GATUN LAKE AND MIRAFLORES LAKE
DAILY SPILLED AND USED WATER QUANTITIES

WL | DELFT HYDRAULICS

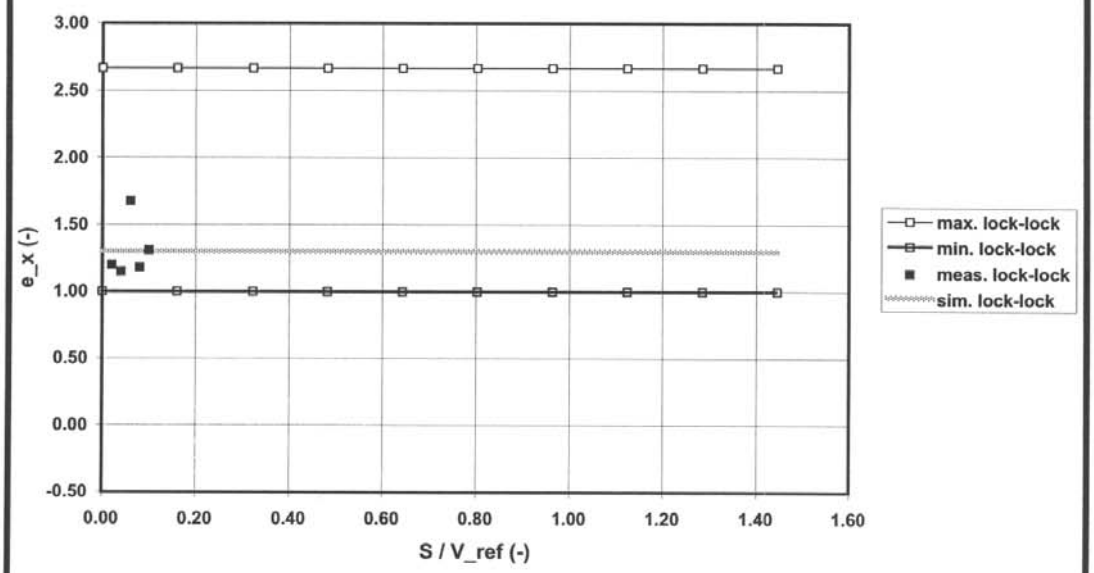
Q 3039

Fig. 5.6

Exchange coefficients uplockage, step I, sea - lock

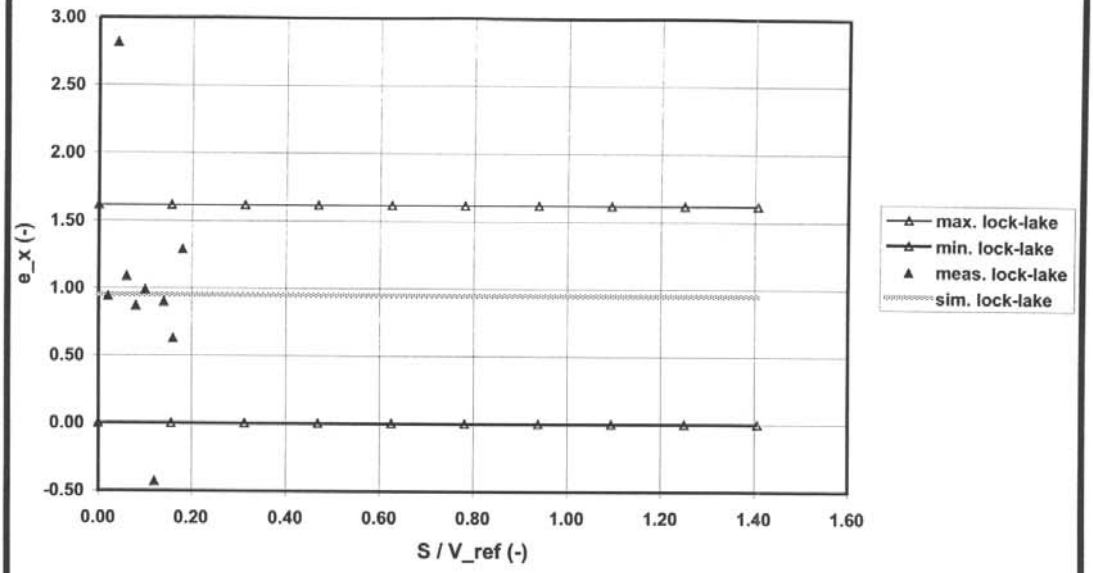


Exchange coefficients uplockage, step I, lock - lock

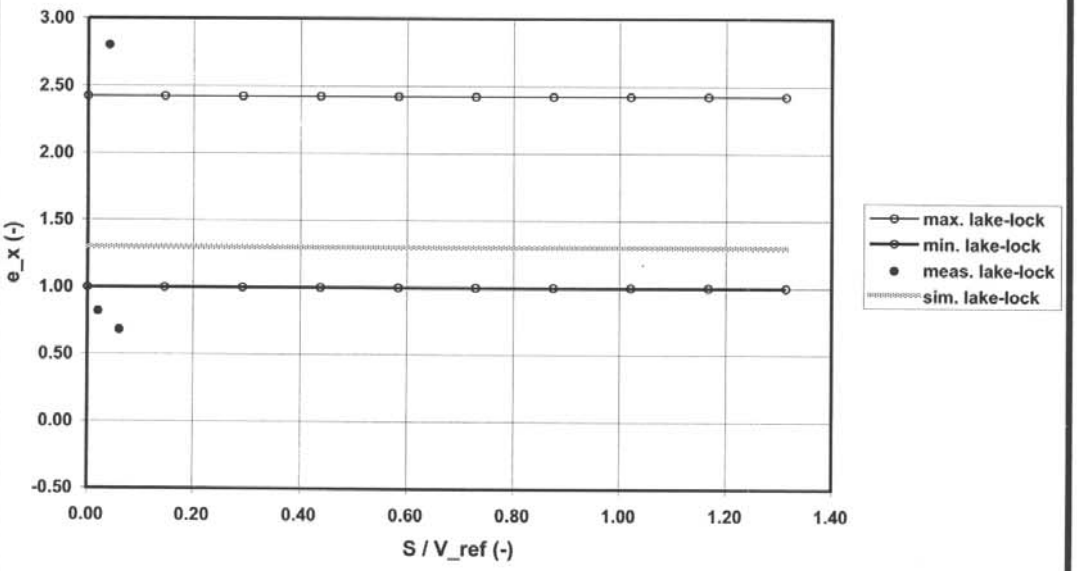


EXCHANGE COEFFICIENTS UPLOCKAGE, STEP I		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.1a/b

Exchange coefficients uplockage, step I, lock - lake

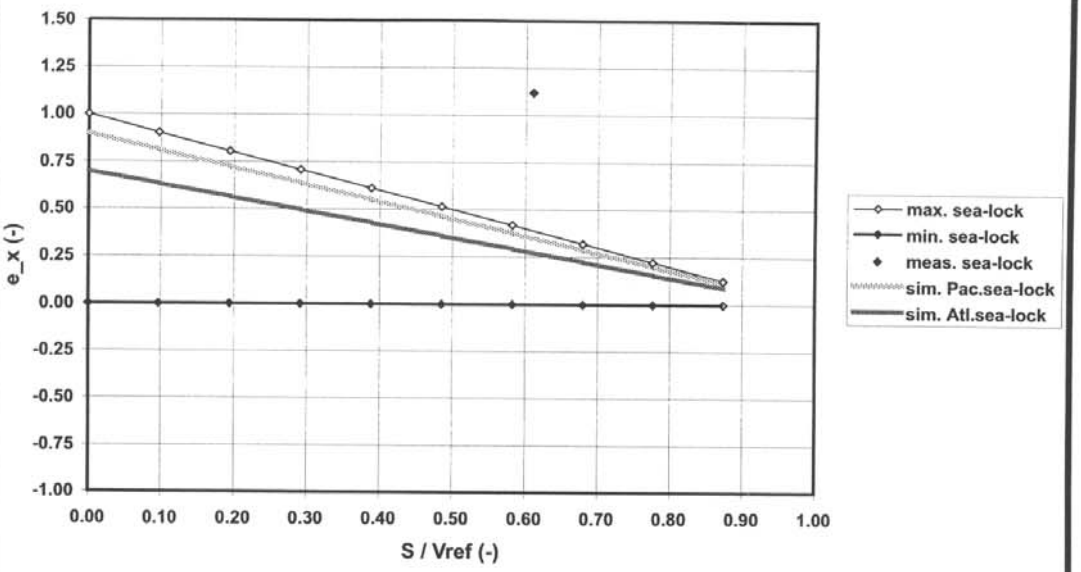


Exchange coefficients uplockage, step I, lake - lock

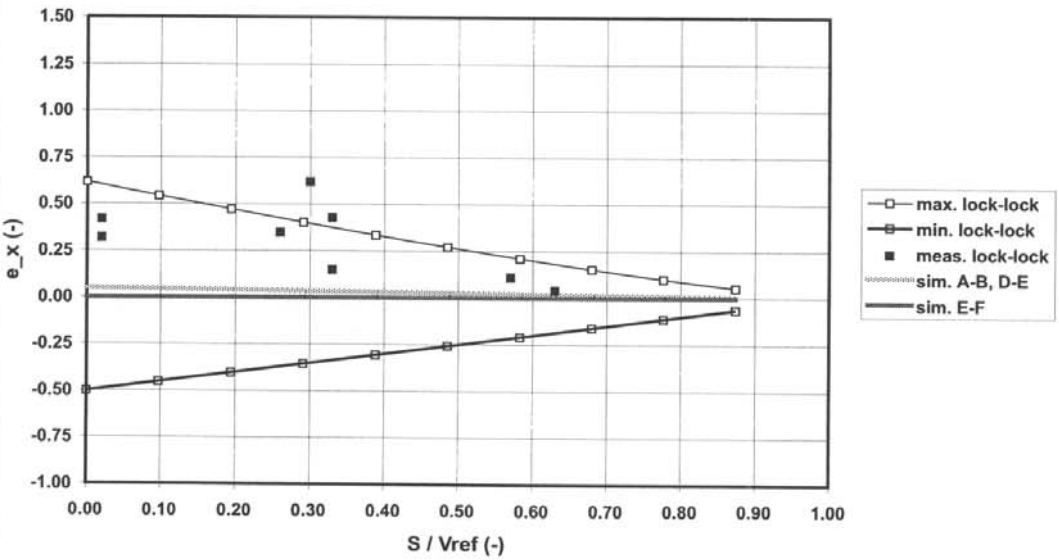


EXCHANGE COEFFICIENTS UPLOCKAGE, STEP I		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.1c/d

Exchange coefficients uplockage, step II, sea - lock

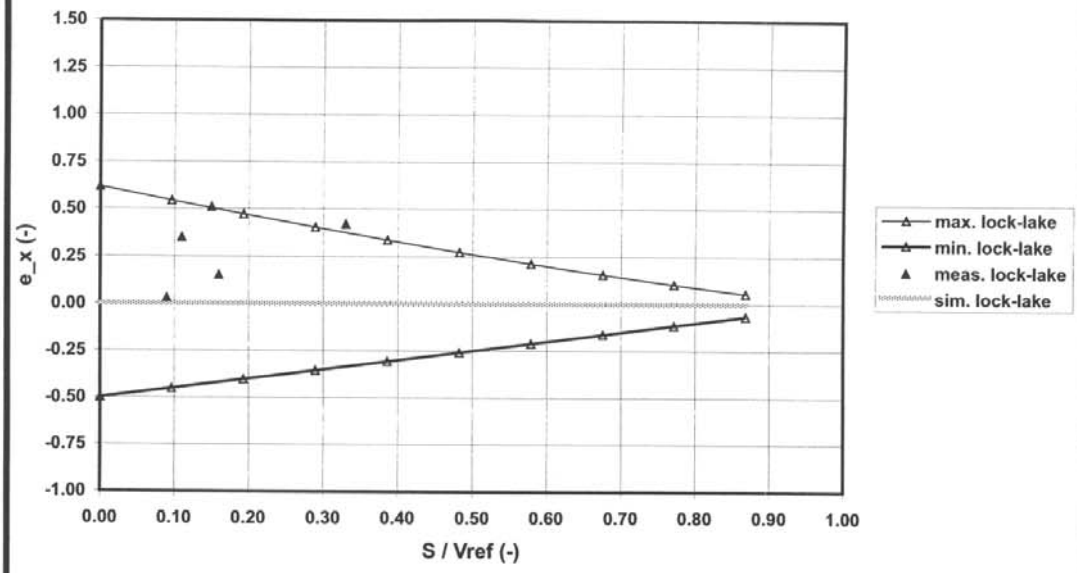


Exchange coefficients uplockage, step II, lock - lock

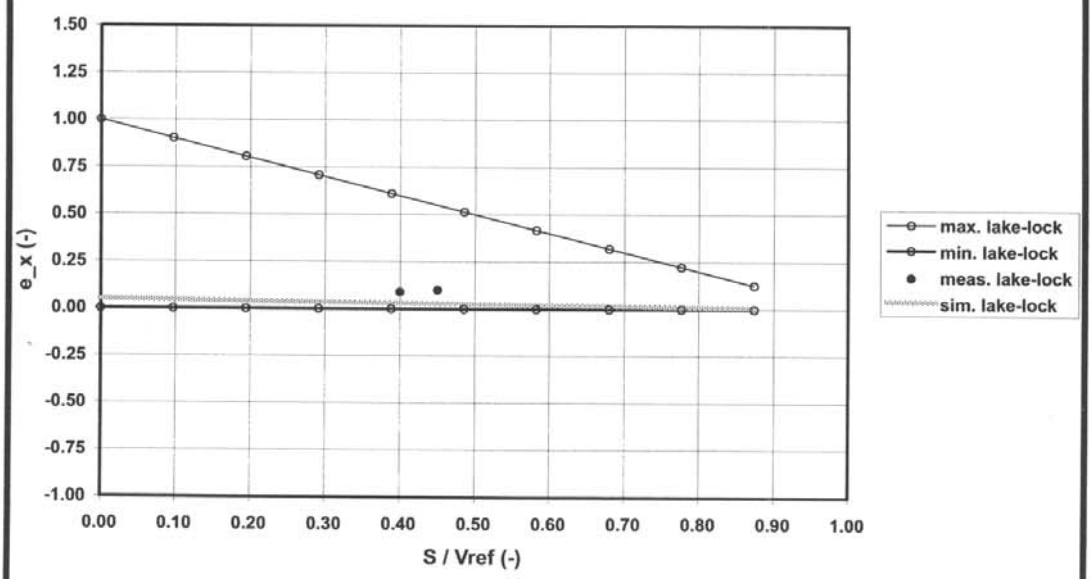


EXCHANGE COEFFICIENTS UPLOCKAGE, STEP II		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.2a/b

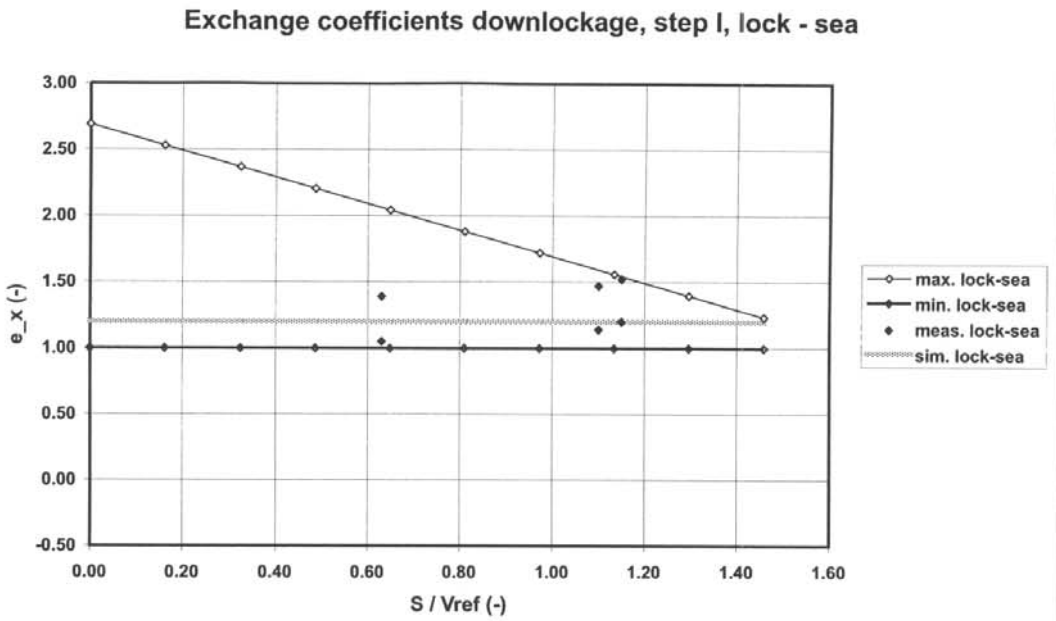
Exchange coefficients uplockage, step II, lock - lake

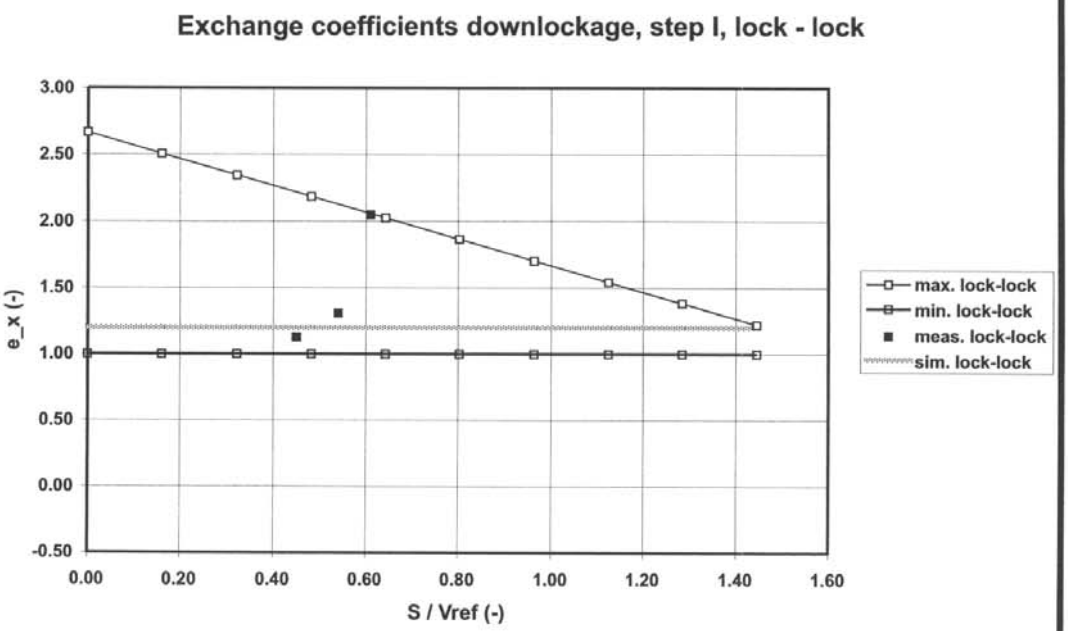


Exchange coefficients uplockage, step II, lake - lock



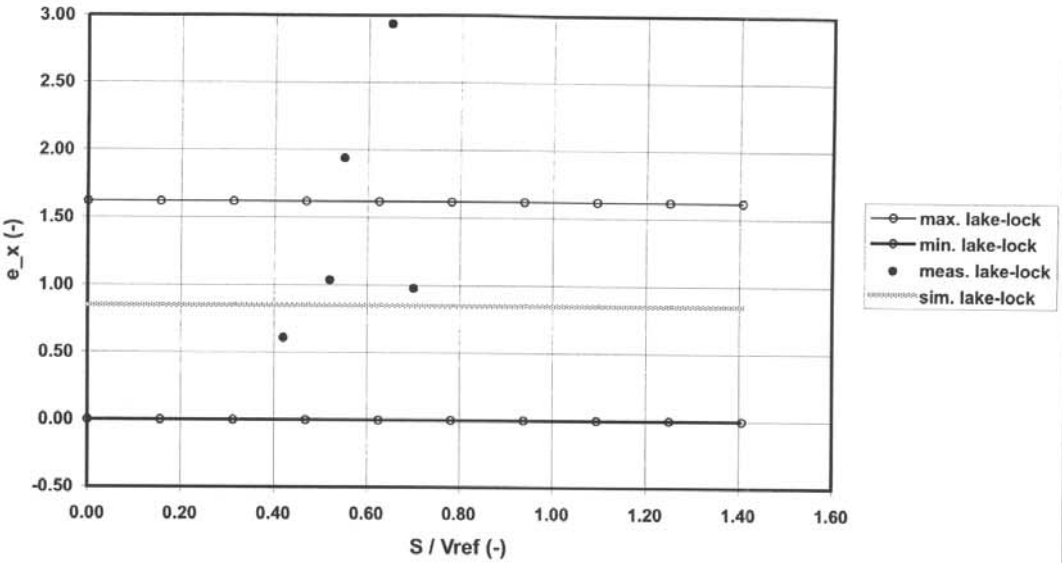
EXCHANGE COEFFICIENTS UPLOCKAGE, STEP II		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.2c/d



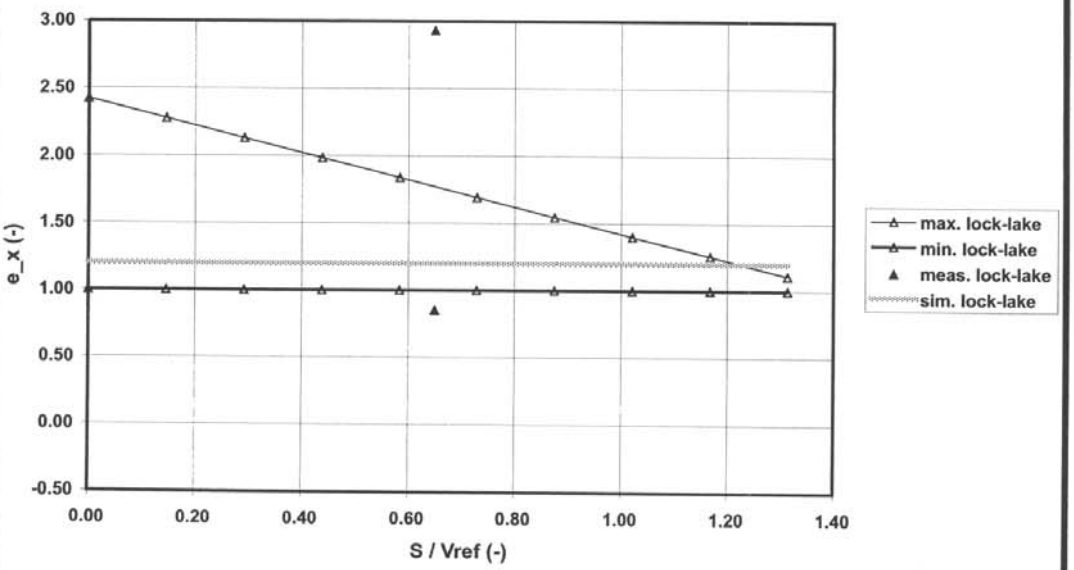


EXCHANGE COEFFICIENTS DOWNLOCKAGE, STEP I		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.3a/b

Exchange coefficients downlockage, step I, lake - lock

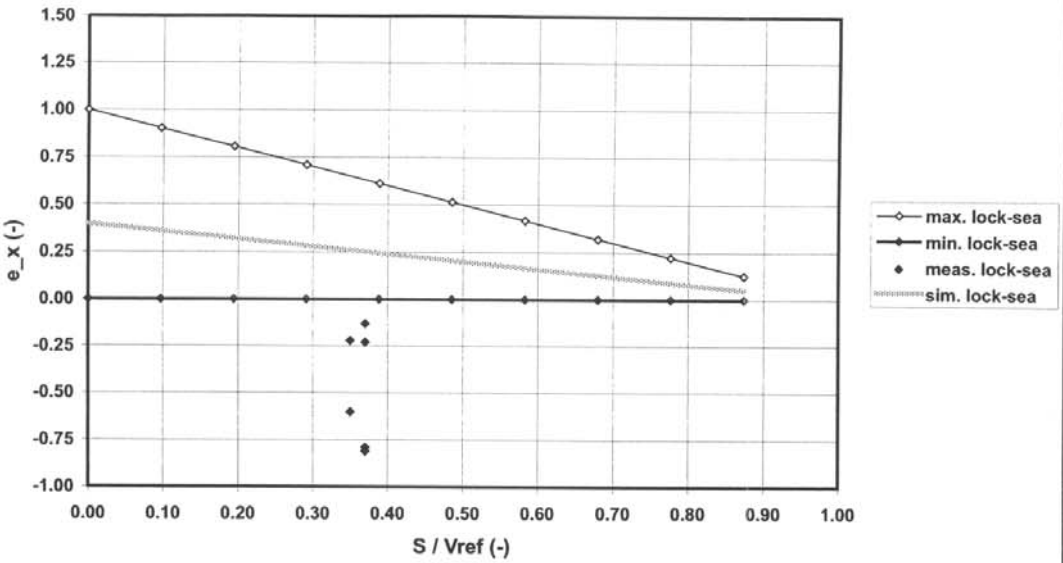


Exchange coefficients downlockage, step I, lock - lake

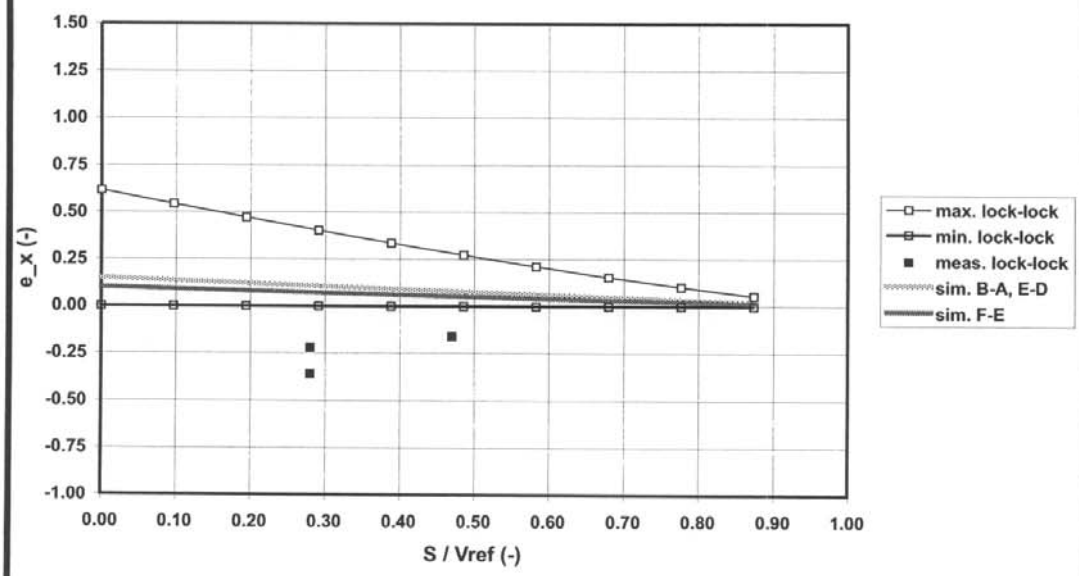


EXCHANGE COEFFICIENTS DOWNLOCKAGE, STEP I		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.3c/d

Exchange coefficients downlockage, step II, lock - sea

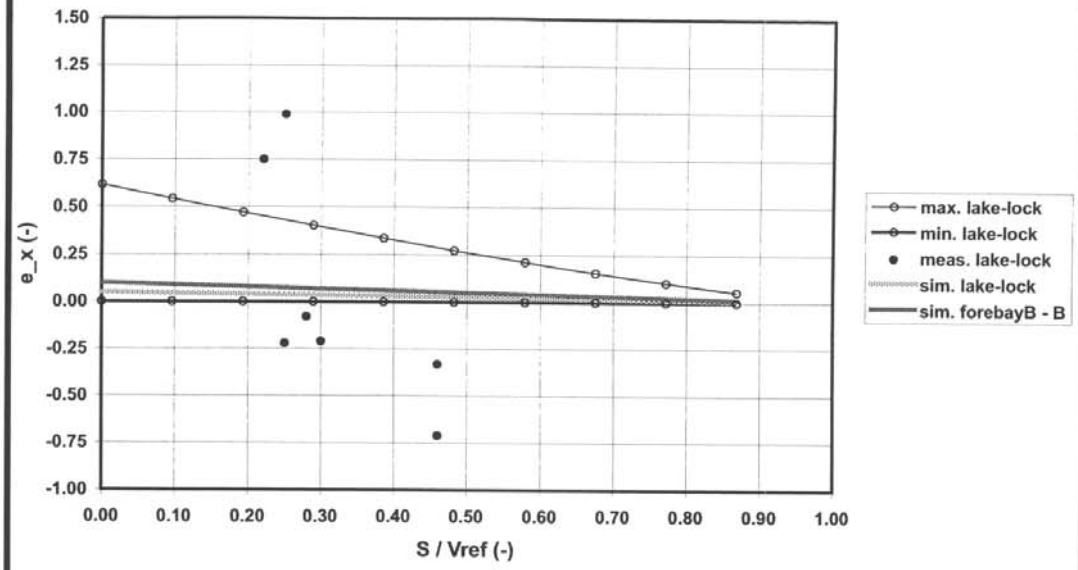


Exchange coefficients downlockage, step II, lock - lock

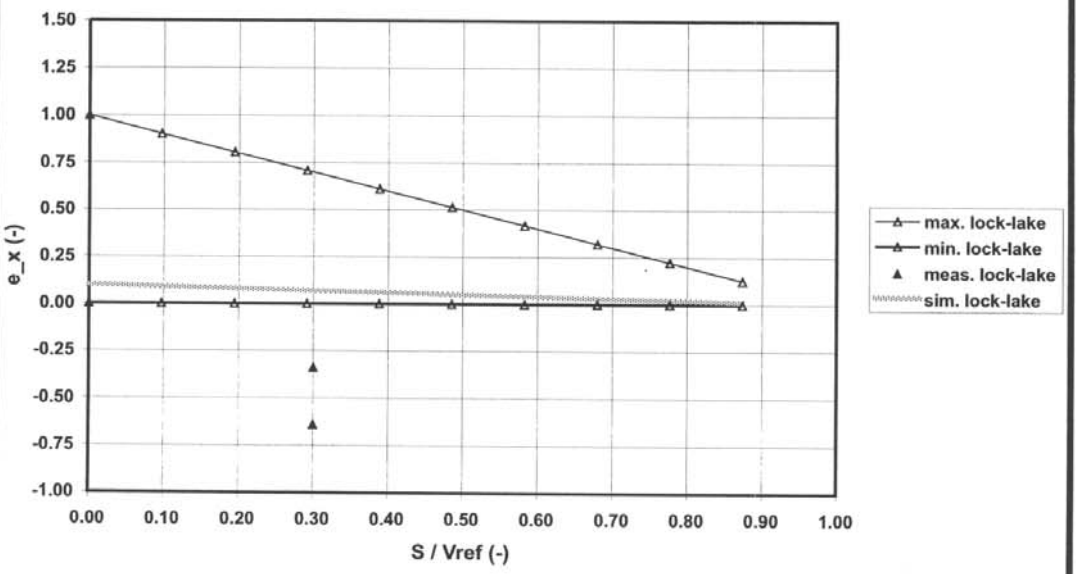


EXCHANGE COEFFICIENTS DOWNLOCKAGE, STEP II		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.4a/b

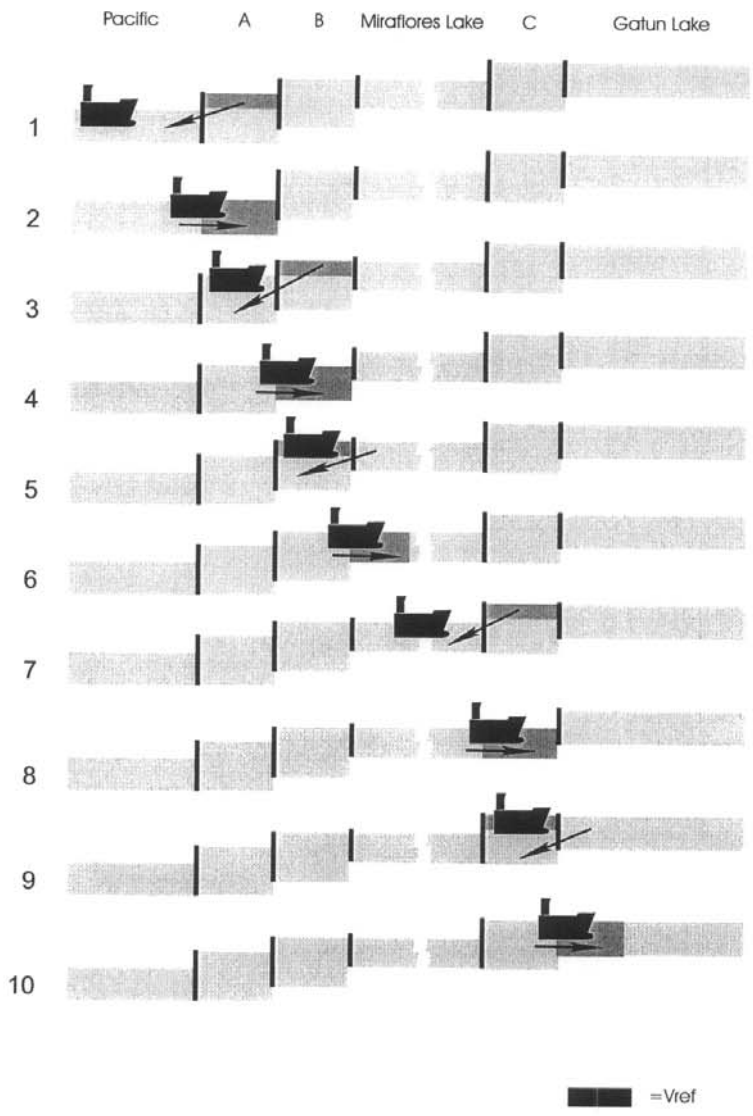
Exchange coefficients downlockage, step II, lake - lock



Exchange coefficients downlockage, step II, lock - lake



EXCHANGE COEFFICIENTS DOWNLOCKAGE, STEP II		
WL | DELFT HYDRAULICS	Q 3039	Fig. 6.4c/d

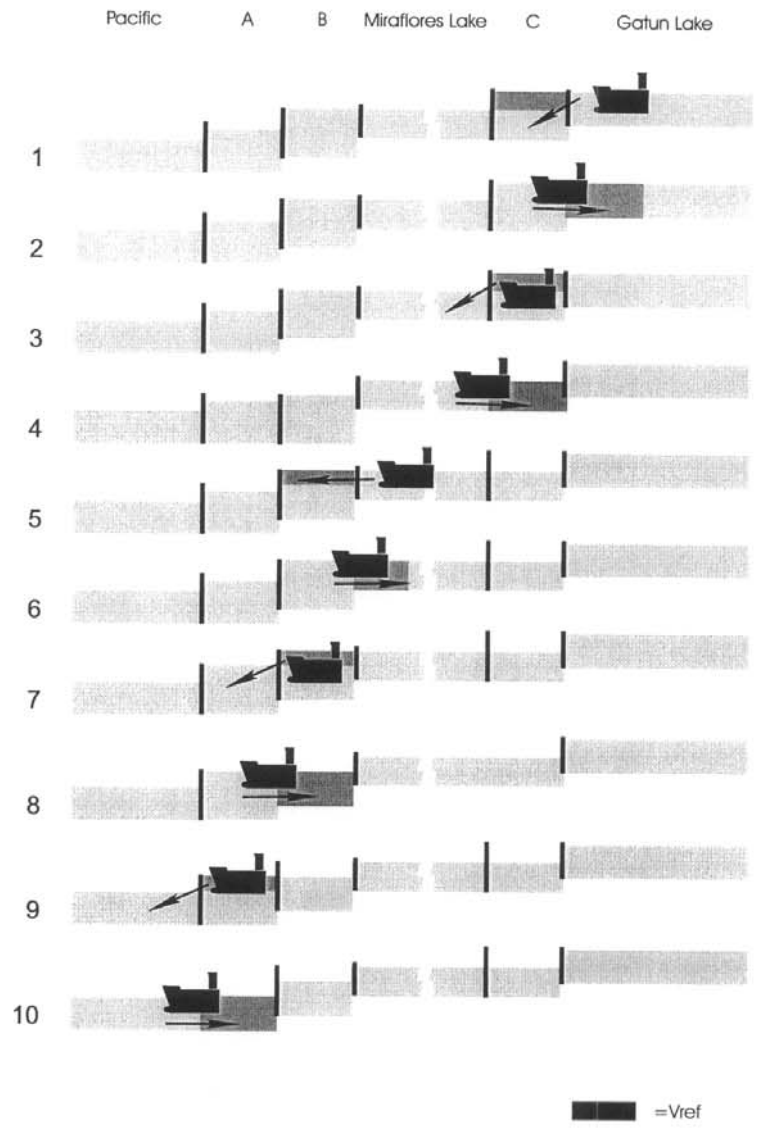


UPLOCKAGE
SHIP MOVEMENT PACIFIC OCEAN - GATUN LAKE

WL | DELFT HYDRAULICS

Q 3039

Fig. 6.5

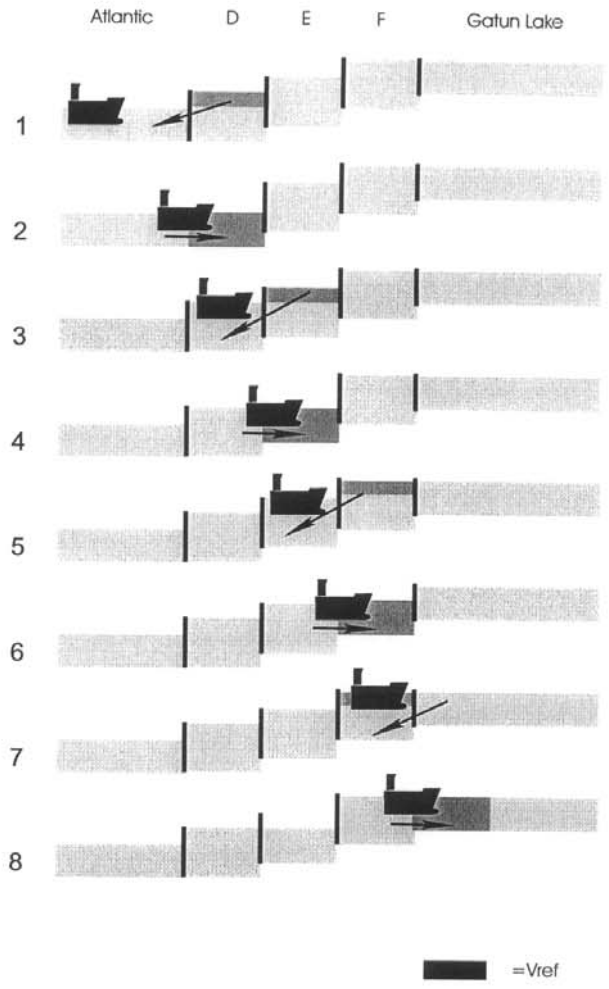


DOWNLOCKAGE
SHIP MOVEMENT GATUN LAKE - PACIFIC OCEAN

WL | DELFT HYDRAULICS

Q 3039

Fig. 6.6

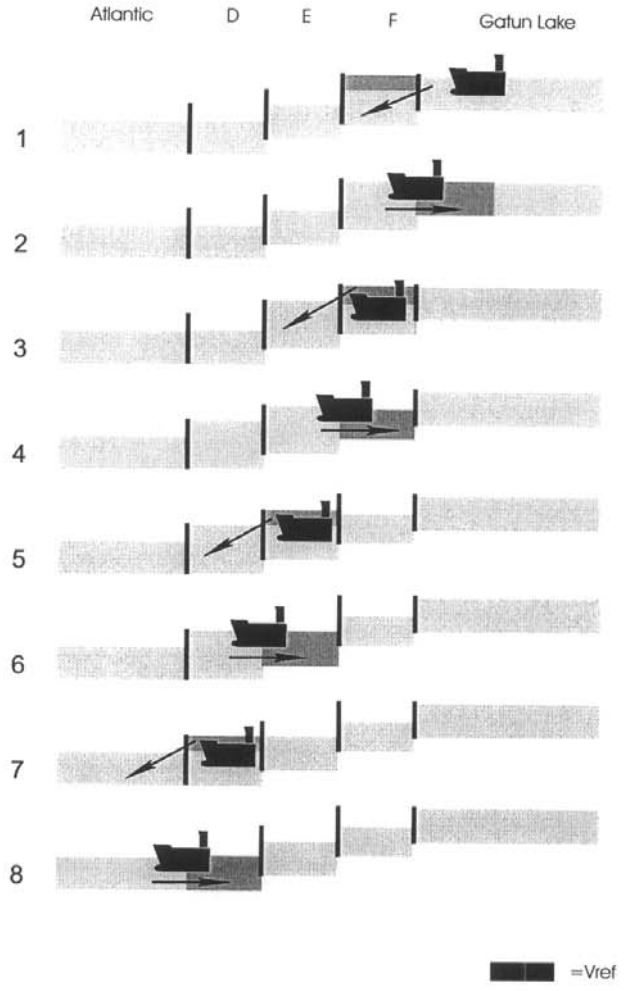


UPLOCKAGE
SHIPMOVEMENT ATLANTIC OCEAN - GATUN LAKE

WL | DELFT HYDRAULICS

Q 3039

Fig. 6.7

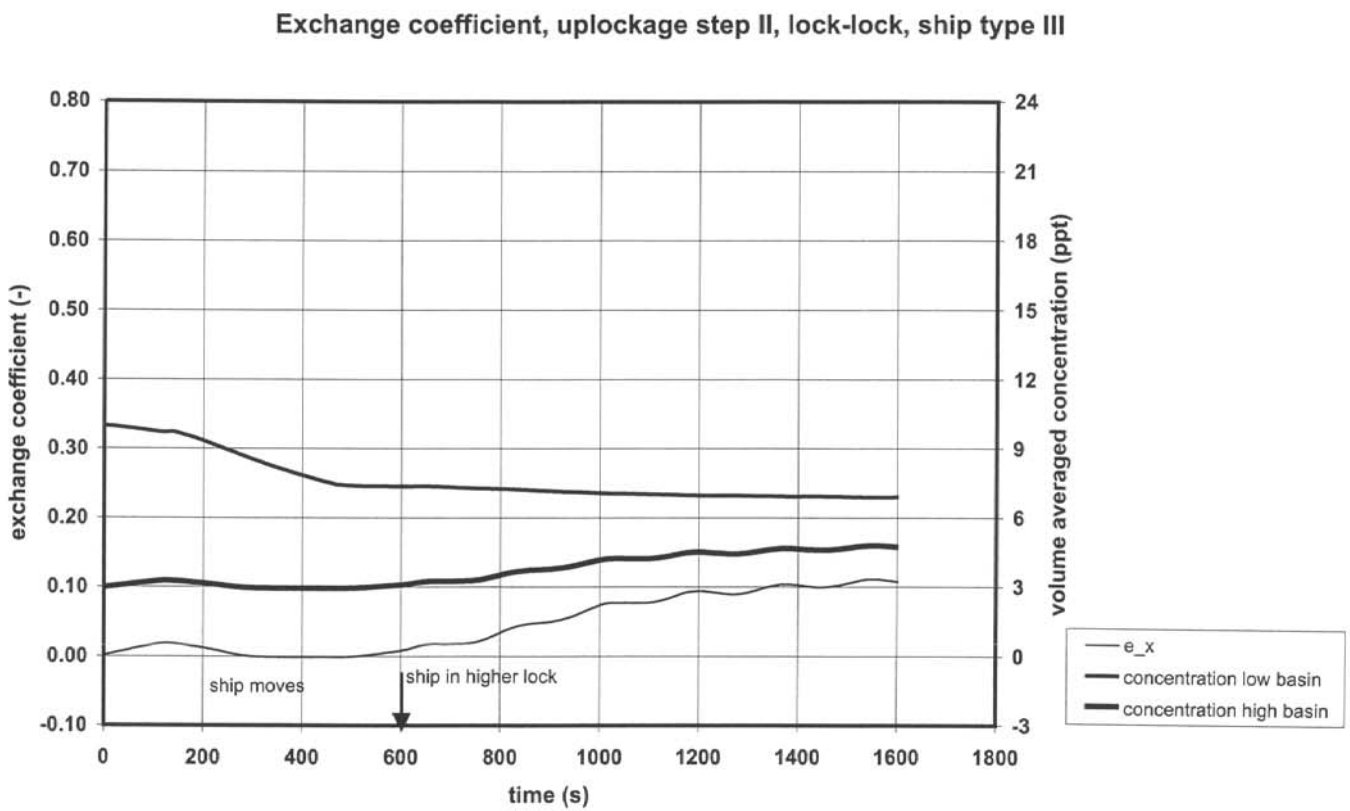


DOWNLOCKAGE
SHIP MOVEMENT GATUN LAKE - ATLANTIC OCEAN

WL | DELFT HYDRAULICS

Q 3039

Fig. 6.8

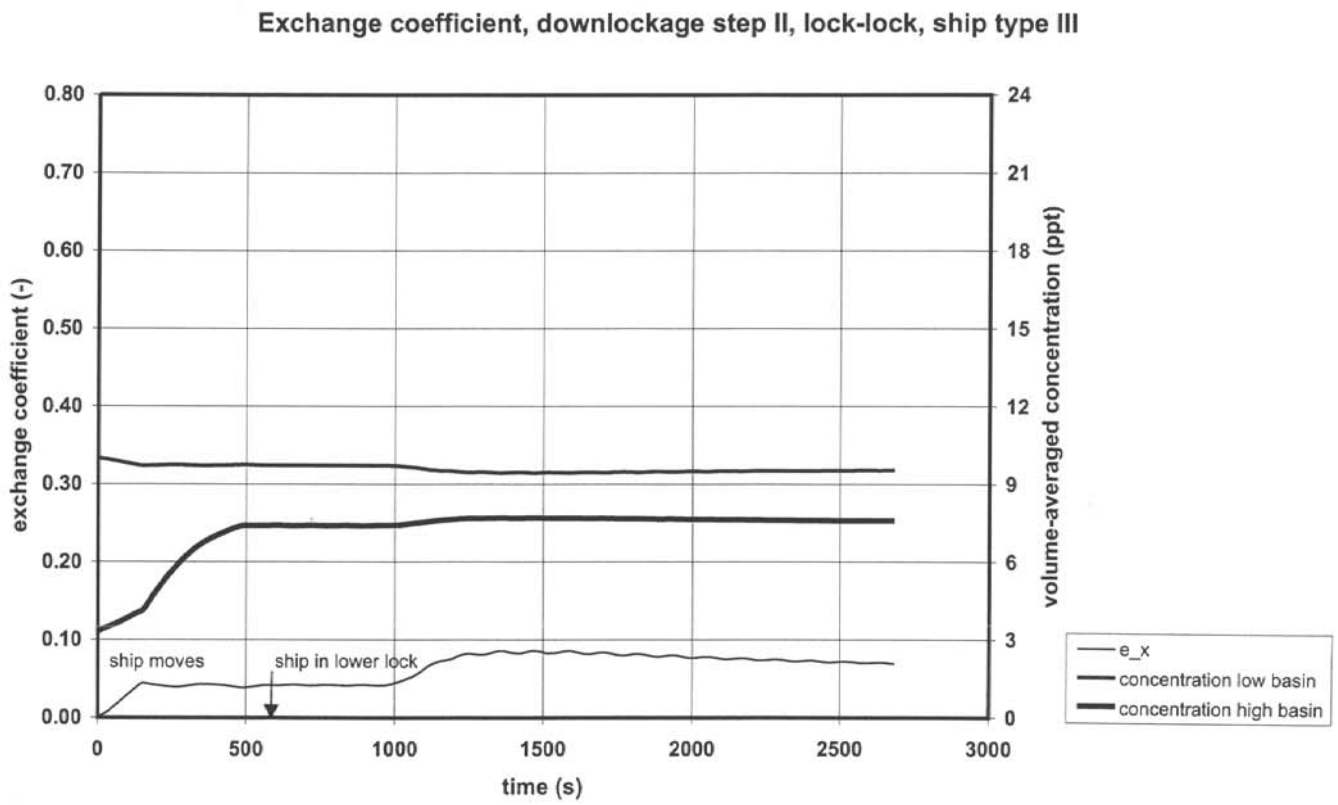


Results of Delft3D computation
Exchange coefficient, step II, uplockage, ship type III

WL | DELFT HYDRAULICS

Q 3039

Fig. 6.9a



Results of Delft3D computation
Exchange coefficient, step II, downlockage, ship type III

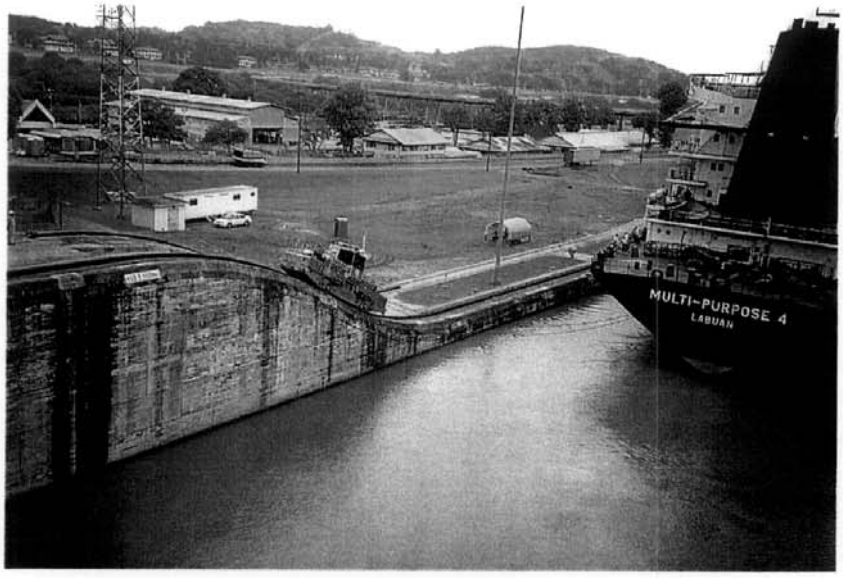
WL | DELFT HYDRAULICS

Q 3039

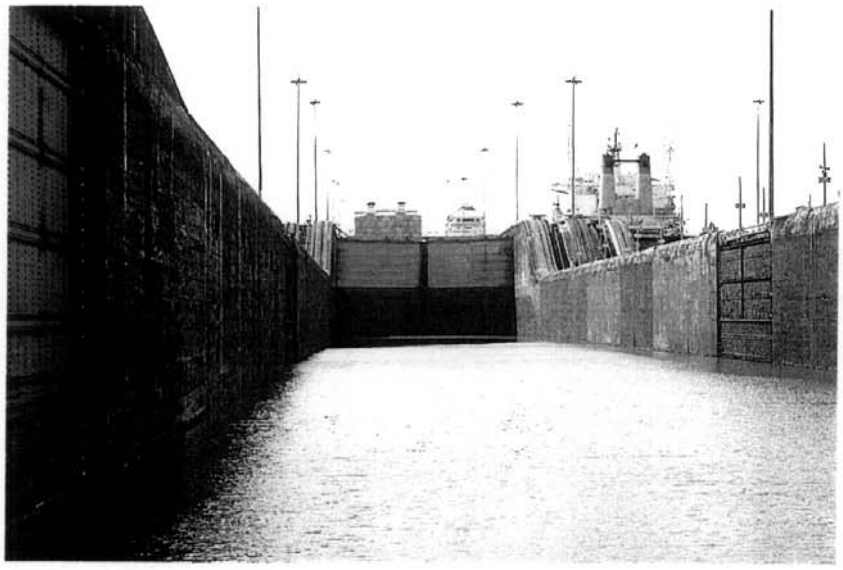
Fig. 6.9b

Photographs

Photograph 1 Gatun Locks. View from control house to Atlantic Ocean



Photograph 2 Miraflores Locks. Locomotive on incline of side wall



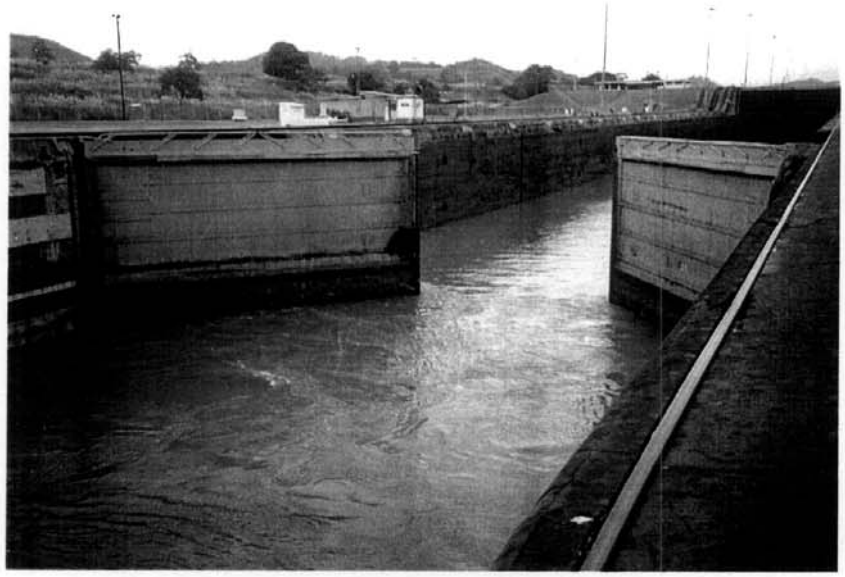
Photograph 3 Lower lock (Lock D) of Gatun Locks

Photograph 4 Measurements in upper lock (Lock B) of Miraflores Locks

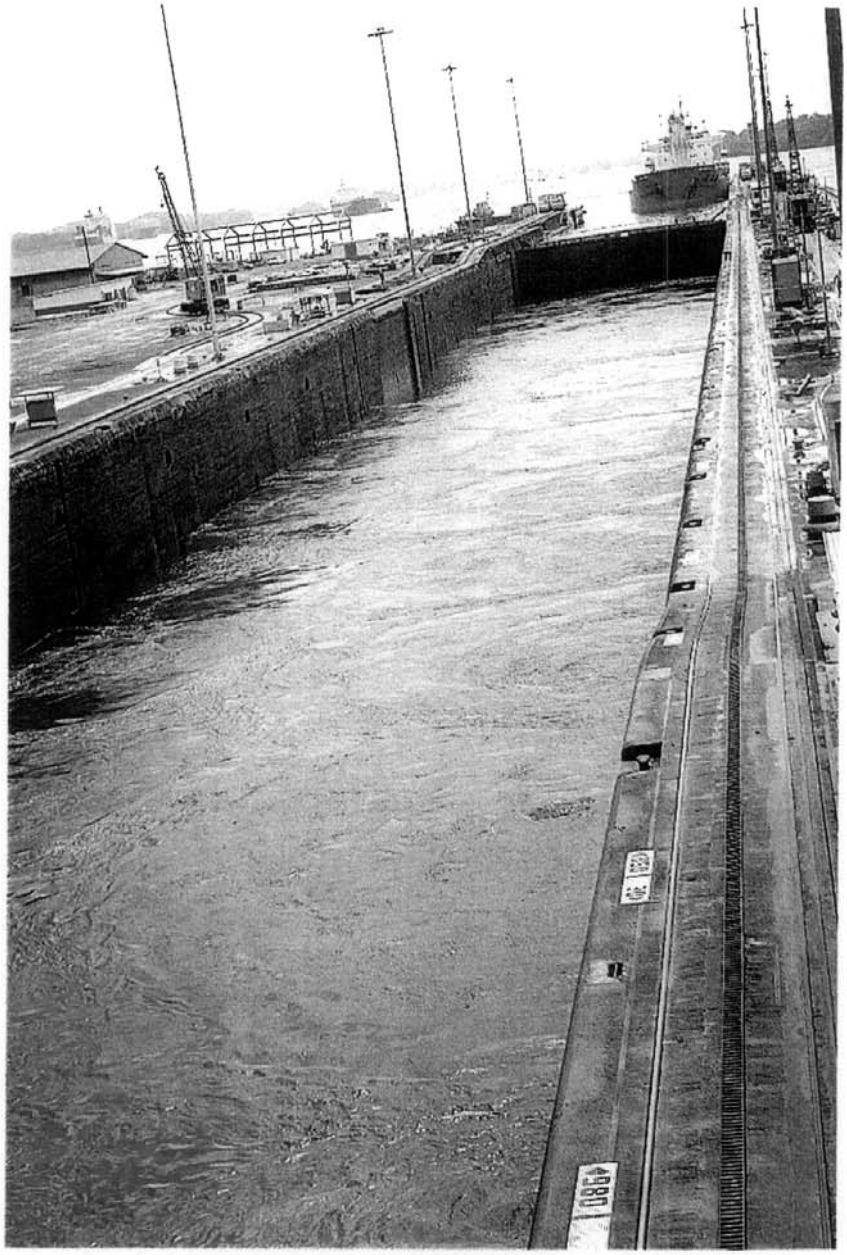
Photograph 5 Measurement of salinities in empty lock chamber

Photograph 6 Measurements behind vessel in lock chamber

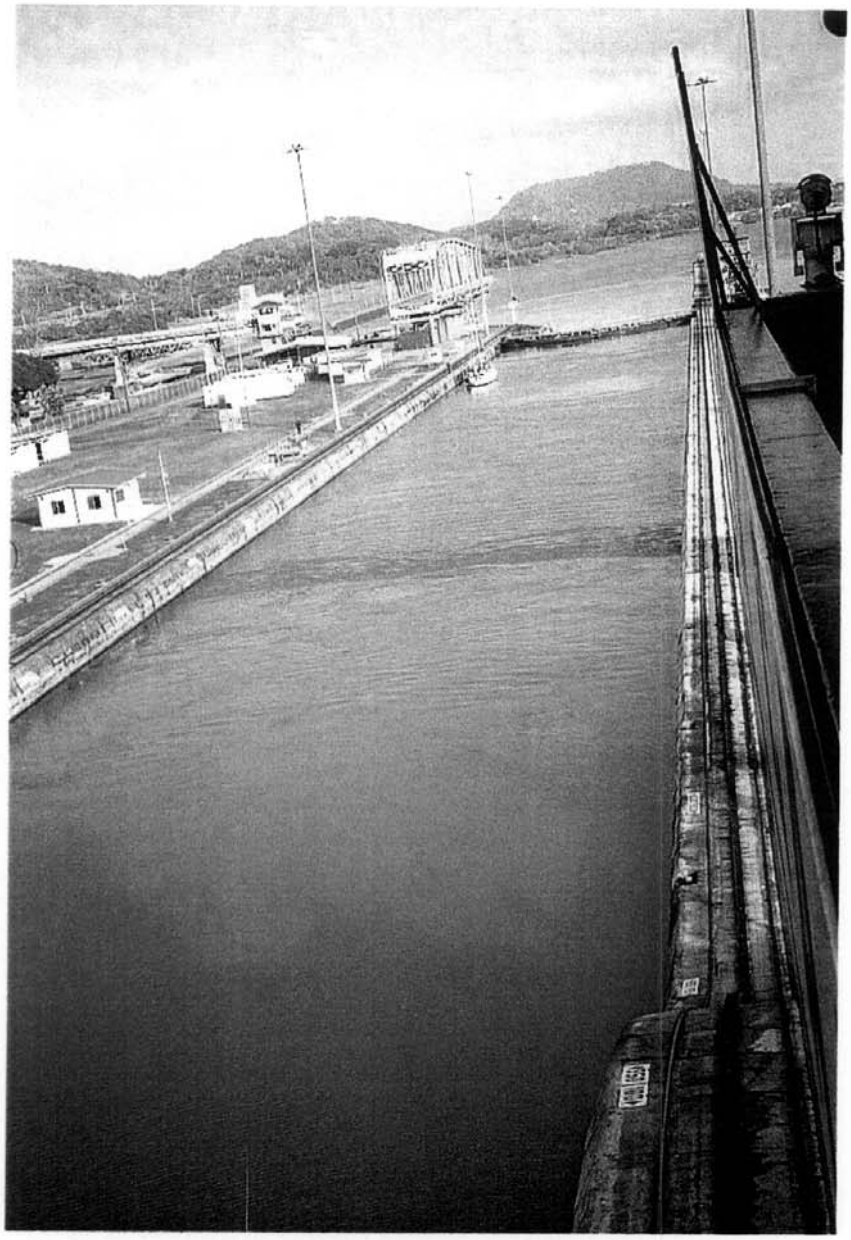
Photograph 7 **Upper lock (Lock F) of Gatun Locks. Exit of vessel with help of pushtow**



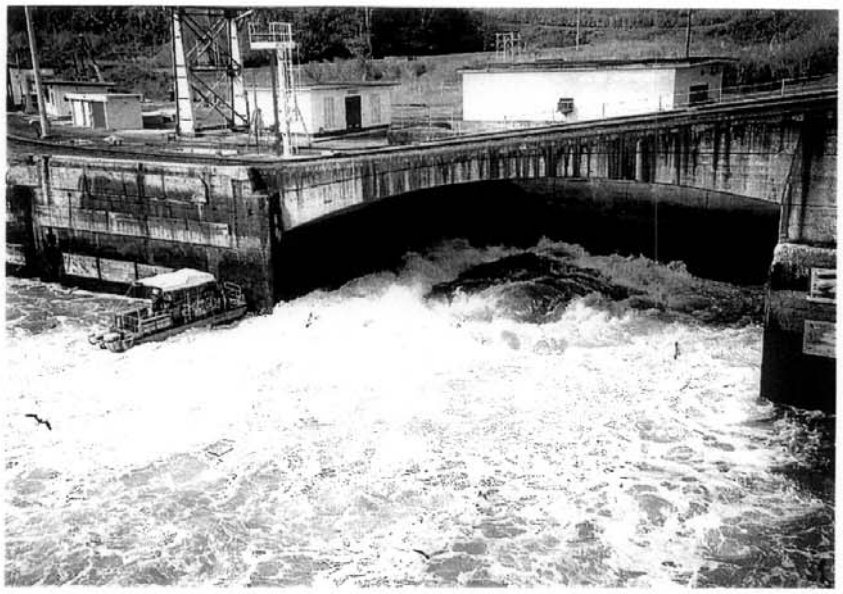
Photograph 8 **Lower lock (Lock A) of Miraflores Locks. Density flow when lock gates are opened**



Photograph 9 Upper lock (Lock F) of Gatun Locks. Filling of lock chamber



Photograph 10 Lower lock (Lock A) of Miraflores Locks. Density flow propagating in lock chamber



Photograph 11 Miraflores Locks. Spillage of water from lower lock (Lock A)

Photograph 12 Miraflores Locks. Outflow of water into tailbay

Figures Simulations

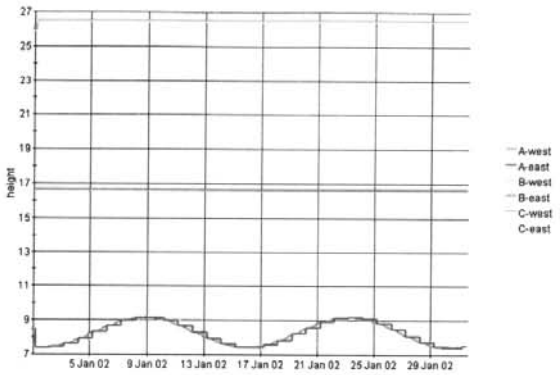


Figure TC1-1 Test case 1. Water levels Locks A, B and C (output interval: scenario)

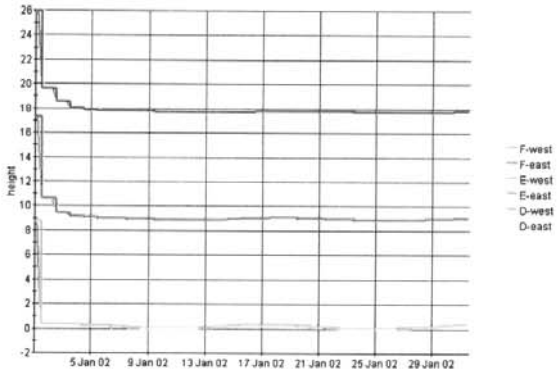


Figure TC1-2 Test case 1. Water levels Locks F, E and D (output interval: scenario)

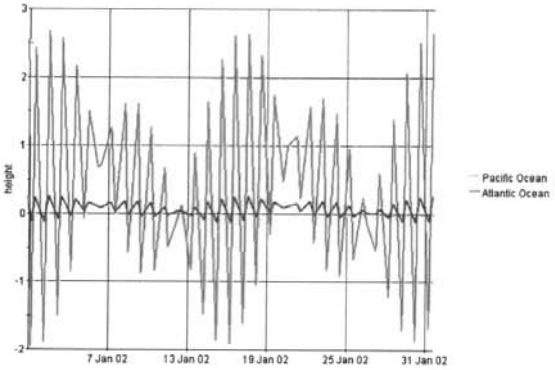


Figure TC1-3 Test case 1. Water levels Pacific and Atlantic tailbay (output interval: scenario)

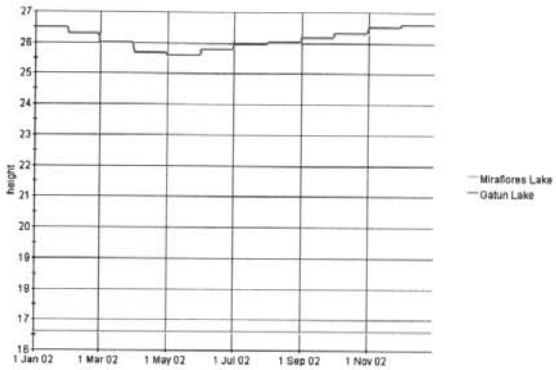


Figure TC3A-1 Test case 3A. Water levels Gatun Lake and Miraflores Lake (output interval: scenario)

Figure TC3A-2 Test case 3A. Concentration Gatun Lake, Miraflores Lake (output interval: scenario)

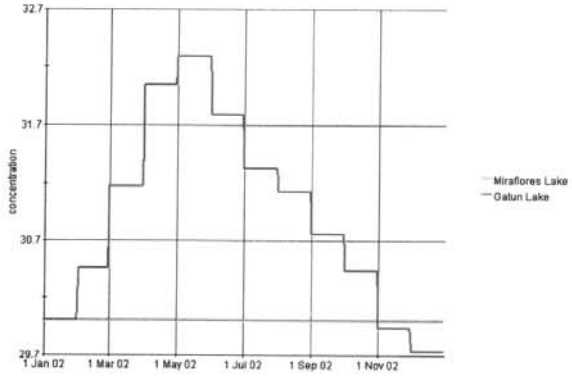


Figure TC3B-1 Test case 3B. Concentration Gatun Lake, Miraflores Lake (output interval: scenario)

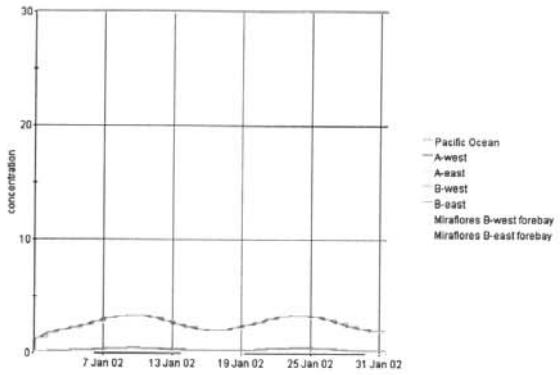


Figure TC7E-1 Test case 7E. Concentration Pac., Lock A, Lock B, B-forebay (output interval: scenario)

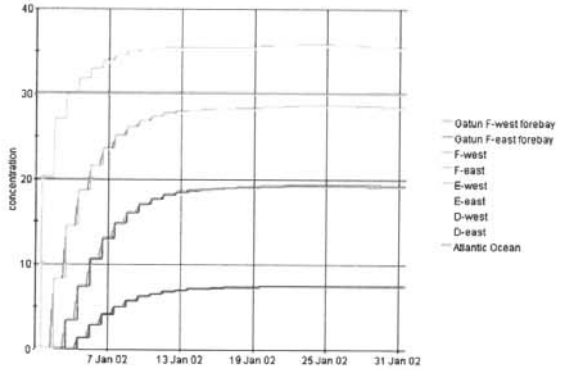


Figure TC7E-2 Test case 7E. Concentration Atl., Lock D, Lock E, Lock F, F-forebay (output interval: scenario)

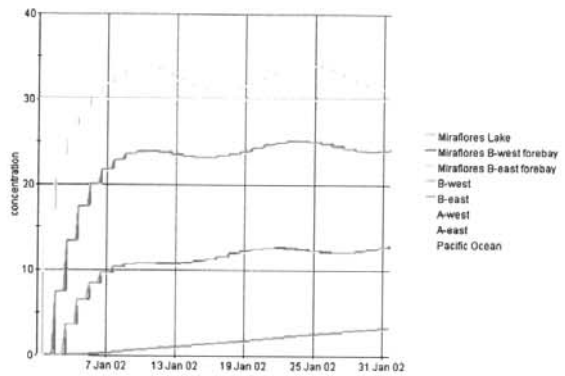


Figure TC7ER-1Test case 7E-R. Concentration Pac., Lock A, Lock B, B-forebay, Miraflores Lake (output interval: scenario)

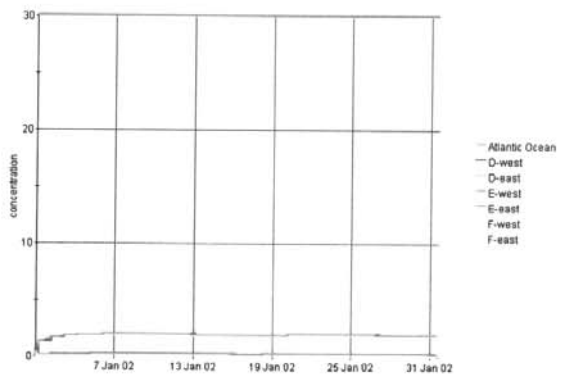


Figure TC7ER-2Test case 7E-R. Concentration Atl., Lock D, Lock E, Lock F (output interval: scenario)

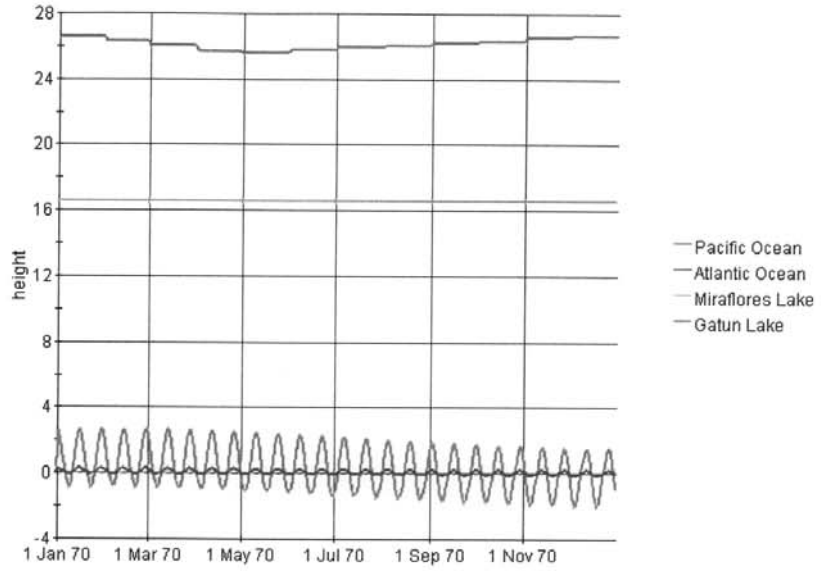


Figure VAL1-1 Validation 1 year. Prescribed tidal movement Pacific and Atlantic tailbay and prescribed water levels Gatun Lake and Miraflores Lake (output interval: day)

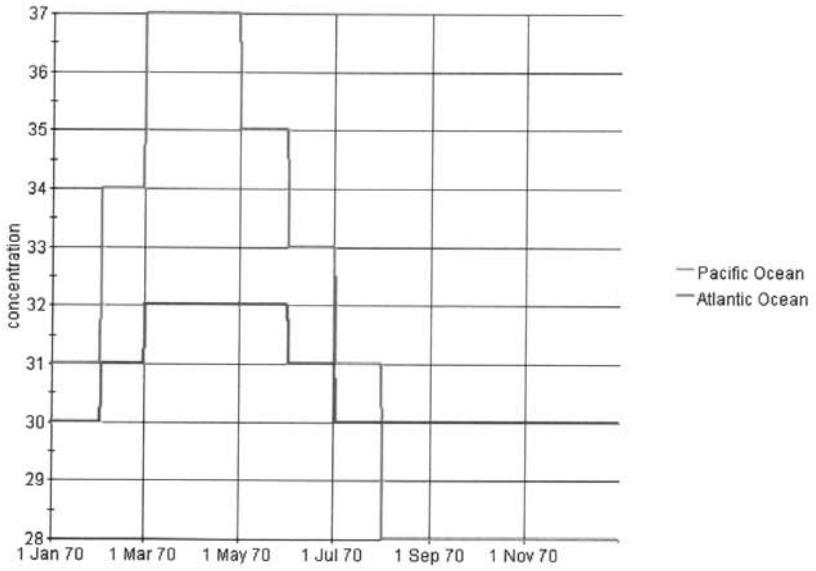


Figure VAL1-2 Validation 1 year. Prescribed concentration Pacific and Atlantic tailbay (output interval: day)

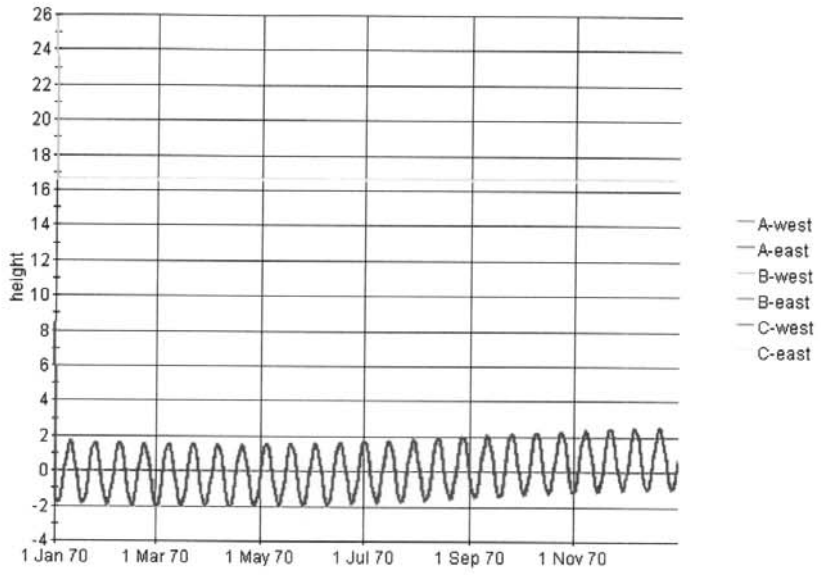


Figure VAL1-3 Validation 1 year. Water levels Lock A, Lock B, Lock C (output interval: day)

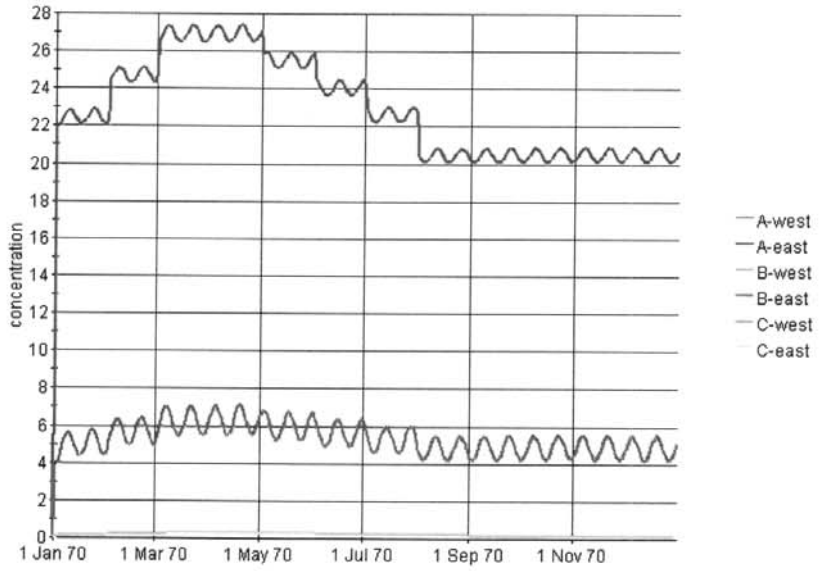


Figure VAL1-4 Validation 1 year. Concentration Lock A, Lock B, Lock C (output interval: day)

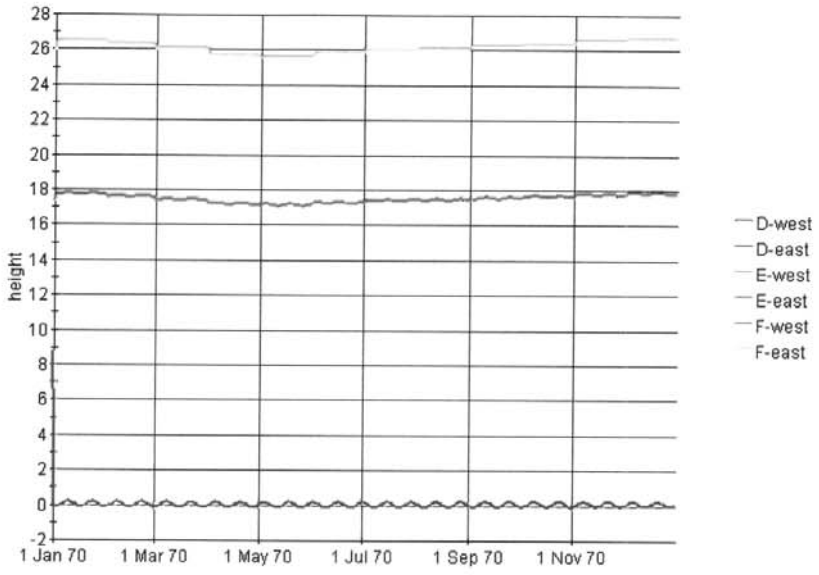


Figure VAL1-5 Validation 1 year. Water levels Lock D, Lock E, Lock F (output interval: day)

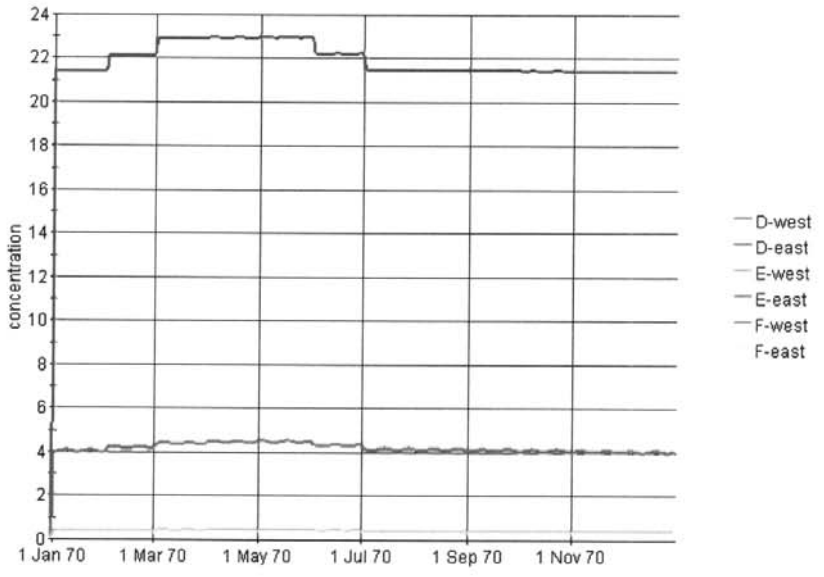


Figure VAL1-6 Validation 1 year. Concentration Lock D, Lock E, Lock F (output interval: day)

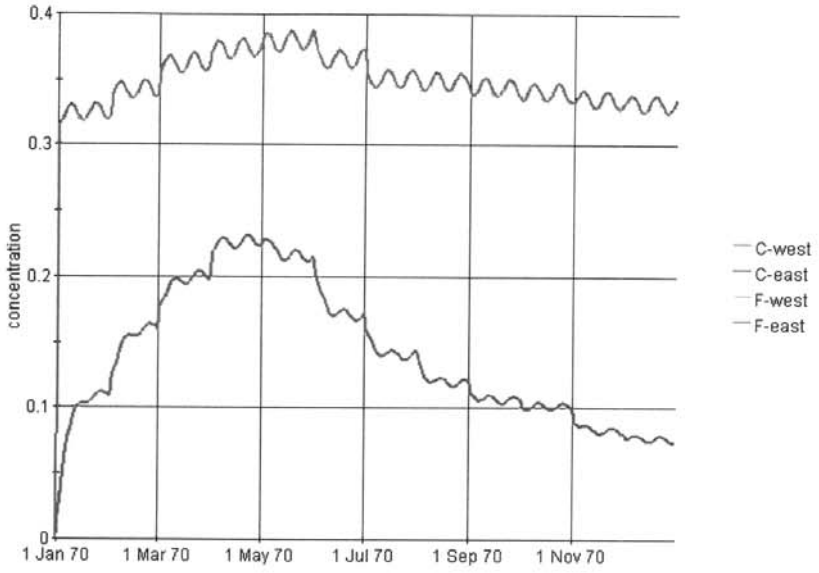


Figure VAL1-7 Validation 1 year. Concentration Lock C and Lock F (output interval: day)

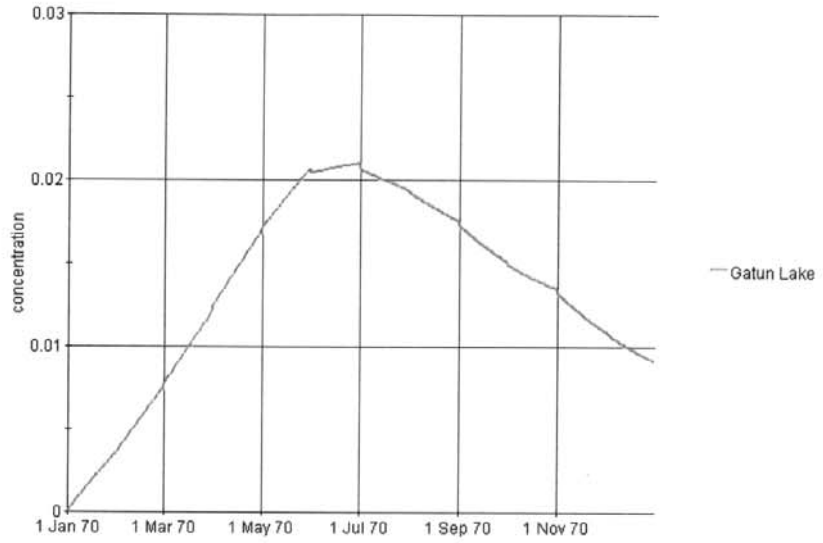


Figure VAL1-8 Validation 1 year. Concentration Gatun Lake (output interval: day)

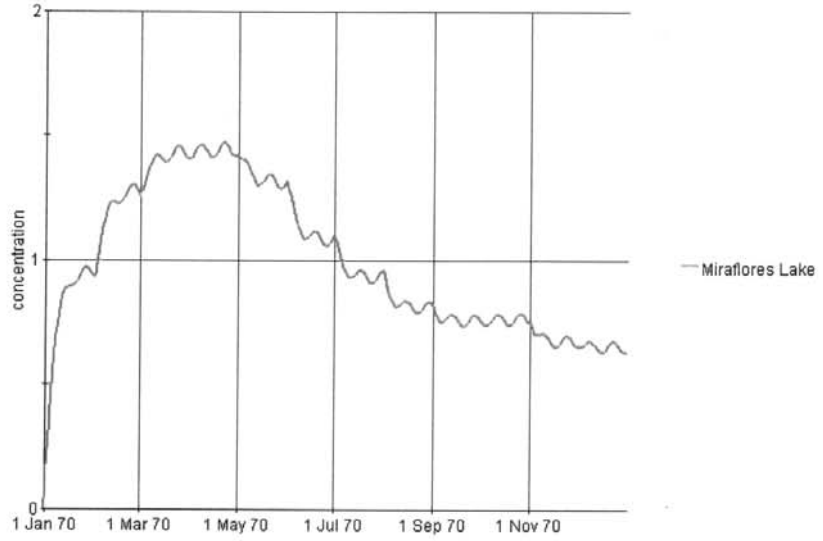


Figure VAL1-9 Validation 1 year. Concentration Miraflores Lake (output interval: day)

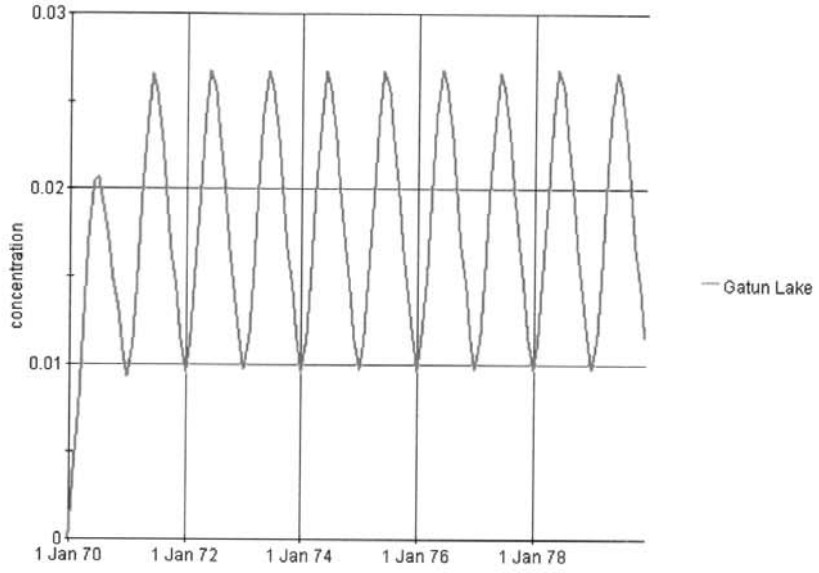


Figure VAL10-1 Validation 10 year. Concentration Gatun Lake (output interval: month)

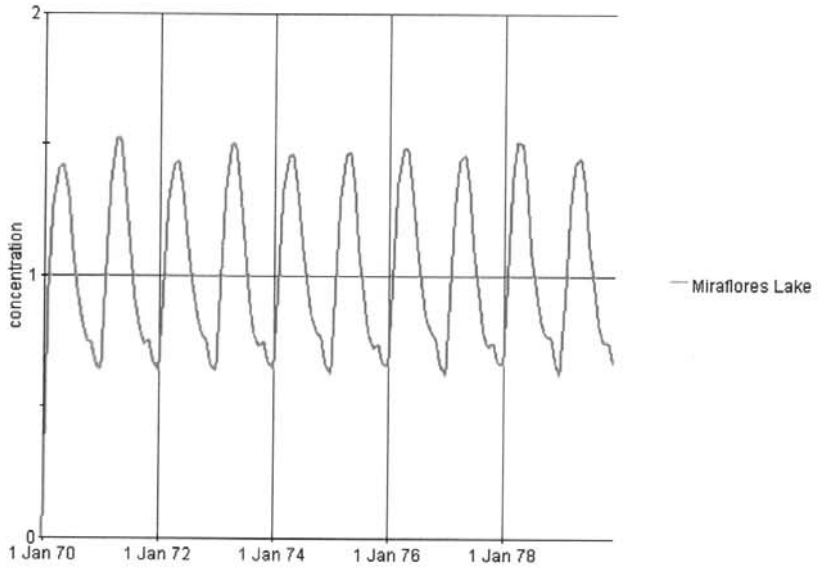


Figure VAL10-2 Validation 10 year. Concentration Miraflores Lake (output interval: month)

Appendix I

Wet Season Data Collection Programme

(Version dated November 2001)

1 Introduction

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 no SAA-74337). The services of WL | Delft Hydraulics that will be executed under the contract, are subdivided in eight major work tasks (see Detailed Project Workplan and Schedule, October 2001). Part of work task 1 is the set up of a programme for data collection on salinity levels and salinity intrusion through the locks in the wet season. This programme is presented in the present report. The wet-season measurements are scheduled for weeks 48 - 50, 2001.

2 Design of the measurements in the wet season

2.1 Aim of the measurements

The Atlantic Ocean is connected to the Pacific Ocean by means of the Panama Canal. Shipping locks at both sides of the canal enable the transfer of ships. The water-level difference of about 26 m between the high, fresh-water Gatun Lake and the Atlantic Ocean is surmounted by means of a three-lift lock system. At the Pacific side a two-lift lock system has been constructed between the Pacific Ocean and Miraflores Lake; a single lift lock forms the connection between Miraflores Lake and Gaillard Cut.

Lock operation at both sides of the Panama Canal may cause an intrusion of salt water from the Atlantic Ocean in the north and the Pacific Ocean in the south. In the past some measurements of salinity levels at various locations in the canal system have been carried out, but neither a full insight in present salinity levels in Gatun Lake, Miraflores Lake and other parts of the canal exists, nor is in sufficiently detail known how salt water intrudes through lock operation.

The aim of the measurements presented in this wet-season data collection programme is:

- to get insight in the hydraulic processes which occur in the locks during operation, including the exchange of water when the lock gates are opened and ships move in and out, mixing of water during filling and emptying and dillution,
- to measure salinity levels and gradients in the approach harbours,
- to measure salinity levels in Miraflores Lake, Gaillard Cut and Gatun Lake.

These measurements will be undertaken in the wet season (in the period end of November - mid December 2001), when the water level in Gatun Lake is high, and will be repeated in the dry season (April 2002). The dry-season measurement programme will be set up after analysis of the measurements of the wet season, so as to take into account the experiences and insights obtained through the wet-season measurements.

2.2 Hydraulic conditions and lock operation

The mean level in Gatun Lake and Gaillard Cut is 25.9 m above datum. The lake level varies in dependence of either dry or wet season (dry season January – April). The high level at the end of the wet season is about +26.7 m (+87.5 ft). When the water level exceeds +26.7 m, the surplus is spilled through Gatun dam. The low level at the end of the dry season is about +25.5 m (+83.7 ft); the minimum level in a dry year, however, can be lower. Restrictions are imposed on locking operations when the water level drops below +24.85 m (+81.5 ft). Water level decrease during the year is caused by lockages, hydropower, use of water for households, aggriculture and industry, and evaporation. The water level in Gatun Lake may have effect on salt water intrusion. It is also therefore that salinity measurements will be executed both at the end of the wet season and the dry season.

The level of Miraflores Lake between Pedro Miguel locks and Miraflores locks is almost constant during the year. The loss of water through Pedro Miguel locks is somewhat greater than the loss of water through Miraflores locks. When the water raises above a maximum level a gated spillway beside the Miraflores locks is used to sluice the water into the approach channel at the Pacific side.

The tidal variation at the Atlantic side is very moderate, 1.0 m maximum. The tidal variation at the Pacific side is considerable (extreme water levels are -3.44 m and +3.60 m); this can have effect on the intrusion of salt water through the Miraflores locks. In the set up of the measurement programme the Pacific tidal variation will taken into account.

The inlet for the drinking water plant (plant is situated upstream of Miraflores locks) was initially located on the east bank of Miraflores Lake. The inlet was moved to a location upstream of Pedro Miguel locks after it appeared that the water quality was unsufficient (relatively high salinity concentration).

Miraflores and Pedro Miguel Locks at the Pacific side and Gatun Locks at the Atlantic side have a 24-hour working scheme. About fourty to fifty vessels per day transite the canal. One day in advance the Marine Traffic Control Department of ACP prepares a transit schedule for the vessels.
In the morning ships come in both from the Atlantic Ocean and Pacific Ocean. The two shipping lanes are simultaneously used in the same direction. Normally, four times a day the locking direction is changed (directions are referred to as southbound and northbound).

The locks are provided with a floor filling / emptying system, which is served through three main culverts in the central wall and both side walls of the locks. Though possible, exchange of water from locks in one lane to locks in the other lane is not practised. Filling water is always supplied form the lock or basin that is one level higher.

Vessels enter or leave the lock chambers with the help of locomotives, which run on rail parallel to the lock chambers. Large ships need four locomotives at both sides of the lock chamber. The locomotives maintain the vessel in the centerline of the lock chamber and assist in towing and braking. Ships use their propeller or tug boats to proceed.

3 Measurement programme

Salinity measurements shall be done in all locks on the Panama Canal, in the approach channels at the sea sides of the locks, in the approach channels at the upstream sides of the locks, near inlets and outlets of the locks, in Miraflores Lake, in Gaillard Cut and in Gatun Lake. Measurement of vertical profiles of salinity will be done with two, fast response CTD instruments (CTD = conductivity, temperature and depth below water surface). From these measurements both the salinity and the density can be derived as a function of depth below the water surface. These two CTD's may simultaneously be deployed in the locks and the canal area, using two launches, which will be made available by ACP. A third instrument that is connected to a data logger, will be used to measure the salinity at a well chosen, fixed point, first at the Pacific side and later at the Atlantic side. These measurements will serve to record variations during a longer period and as reference source.
Positioning is done with GPS, yielding a horizontal accuracy of typically 5 m. In the locks positioning is done using marks on the lock walls.
Simultaneously with the measurements all other relevant data are collected, including date, wheather conditions, water levels, dimensions and type of ships in locks, and lock operation. The work in the locks and channels will be coordinated by ACP staff.

3.1 Salinity measurements in locks - general

To get insight in the hydraulic processes during locking we will do measurements during all stages of locking, both for ships which are locked up or locked down. These various stages are:

- lock chamber open; water is exchanged because of density differences and because ships enter or leave the chamber,
- lock chamber closed; the water in the lock is levelled either with the upstream lock / basin or downstream lock / basin; the lock chamber is empty or a ship is in the lock chamber; water is supplied or withdrawn by means of the floor filling / emptying system.

Starting points for the measurements in the locks are:

Since East and West lanes are simultaneously used in the same direction, locking processes are similar and there is no need to do separate salinity measurements in each of the two lanes. The choice in which lane measurements will be executed is dependent on traffic and possibilities to fit into the locking scheme.
Ship transit schedules are prepared one day in advance by the Marine Traffic Control Department. In the measurement period transit schedules are normally prepared. In consultation with the Marine Traffic Control Department possibilities of executing measurements are discussed and decided on the basis of the transit schedule for the next day.

All measurements in the locks are done with the help of the launches; these launches will either go ahead a vessel or astern a vessel.

Measurements (vertical profiles of salinity) will be executed in longitudinal sections of the lock chamber prior to the entry of a vessel or after a vessel has left the lock chamber. This will generally give a maximum delay for shipping of 20 minutes. When this is not acceptable, the number of vertical profiles may be reduced to a minimum of three in longitudinal sections, possibly reducing the delay to about 10 minutes.
During entering or leaving of a vessel measurements will be executed at fixed locations near the closed miter gates of the lock chamber (no delay for shipping).
Similar measurements will be excuted in up-lockage and down-lockage conditions.

Five days of measurements are planned for Miraflores Locks and Pedro Miguel Locks in the period 28 November - 5 December and four days for Gatun Locks in the period 7 - 14 December. Balboa will be the home basis for measurements at the Pacific side, Colon the home basis for measurements at the Atlantic side. Transfer from Pacific side to Atlantic side is probably on 6 December. The days planned for the locks need not to be consecutive; the execution of measurements will depend on the possibilities to insert the measurements in the transit schedule.

Lock indication:

Miraflores locks:	A = lower lock, B = upper lock
Pedro Miguel lock:	lock C
Gatun locks:	D = lower lock, E = middle lock and F = upper lock

A step by step description of the measurements in the locks is presented on next pages. Figures have been prepared which show the various steps.

3.2 Measurements in Miraflores Locks and Pedro Miguel Locks

Measurements will take place on five, non-consecutive days, referred to as day A – day E. These days can independently be planned in the transit schedule. The start of measurements of day D should be planned at high tide in the Pacific entrance, day E at low tide.

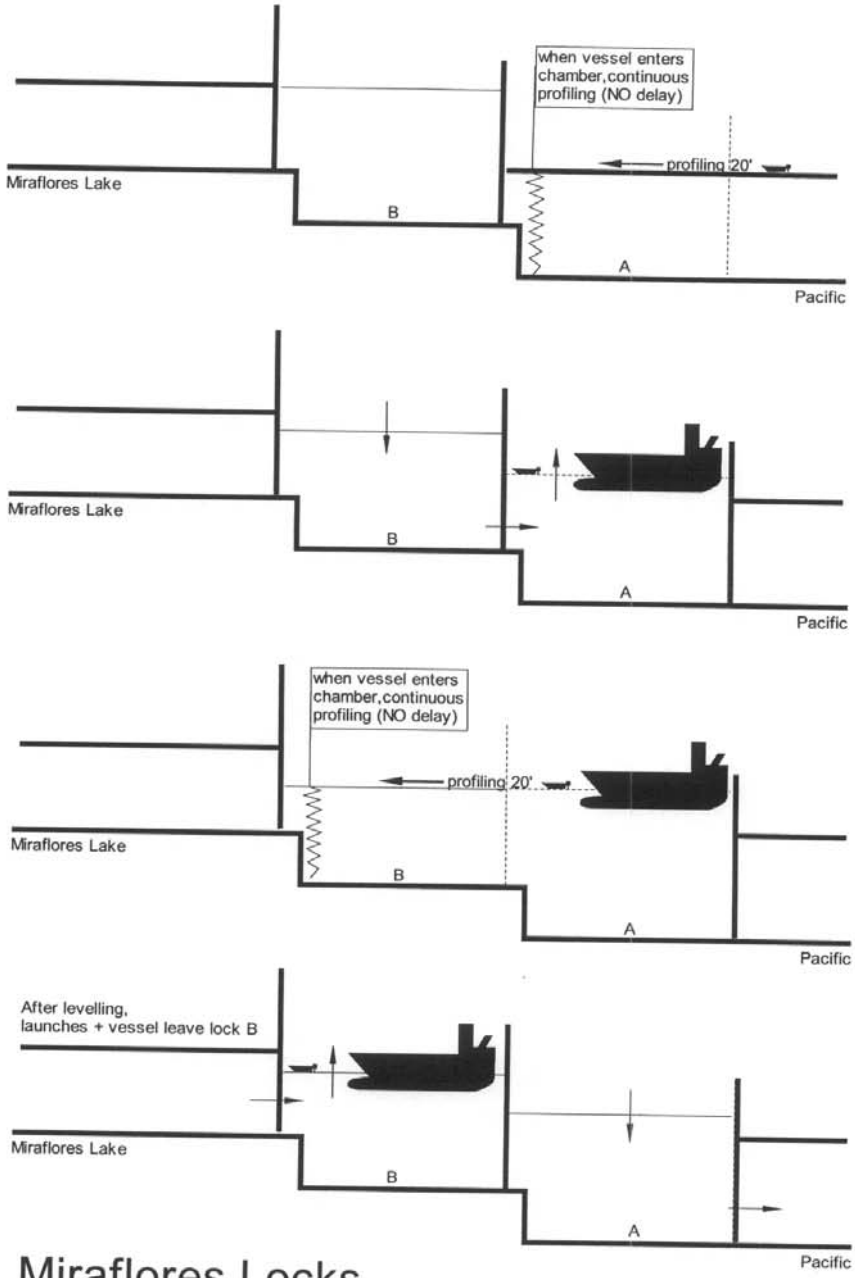
Day A

Morning northbound vessels. Start at downstream side of Miraflores locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	A	low	in lock A; vessel waits	profiling in A max delay 20 min	x	x
2	A		ahead of vessel in lock A	levelling		
3	B	low	in lock B; vessel waits in A	profiling in B max delay 20 min	x	x
4	B		ahead of vessel in lock B	levelling		
5	B	high	ahead of vessel	launches + vessel leave lock B		
6	C	low	in lock C; vessel waits	profiling in C max delay 20 min	x	x
7	C		ahead of vessel in lock C	levelling		
8	C	high	ahead of vessel	launches + vessel leave lock C		

Afternoon southbound vessels. Start at upstream side of Pedro Miguel locks. East lane or West lane.

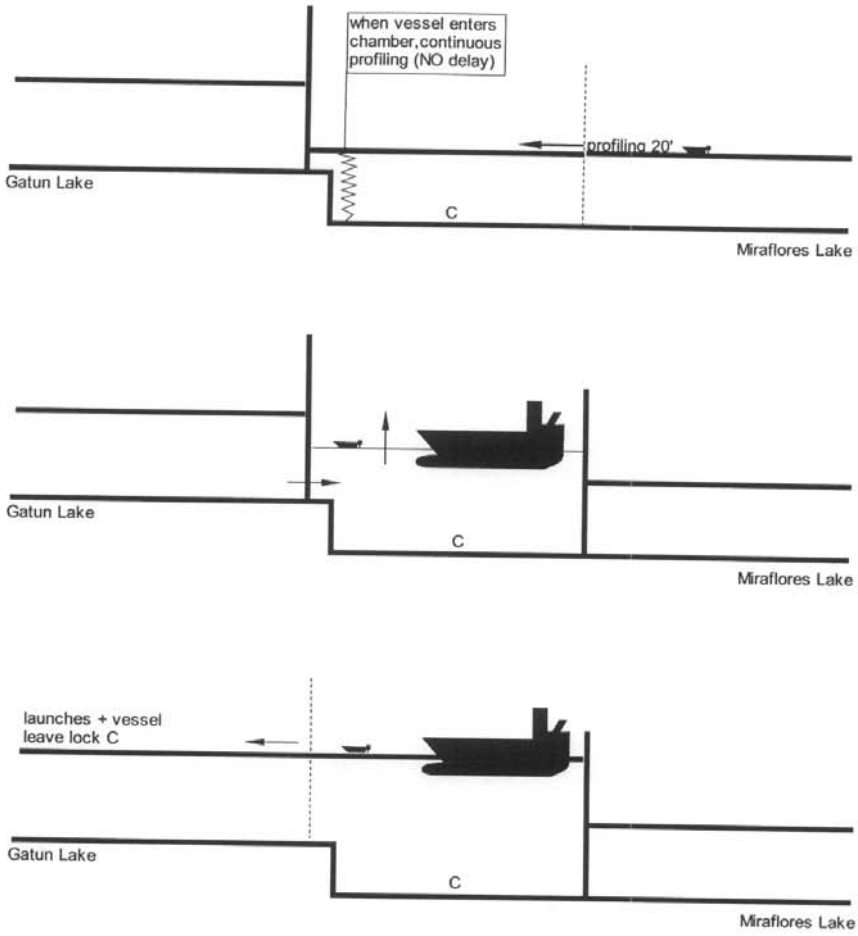
step	lock	water level in lock	position of launches	activity	long sections	positions near gates
9	C	high	in lock C; vessel waits	profiling in C max delay 20 min	x	x
10	C		ahead of vessel in lock C	levelling		
11	C	low	ahead of vessel	launches + vessel leave lock C		
12	B	high	in lock B; vessel waits	profiling in B max delay 20 min	x	x
13	B		ahead of vessel in lock B	levelling		
14	A	high	in lock A vessel waits in B	profiling in A max delay 20 min	x	x
15	A		ahead of vessel in lock A	levelling		
16	A	low	ahead of vessel	launches + vessel leave lock A		



Miraflores Locks

MORNING - NORTHBOUND - AHEAD OF VESSEL

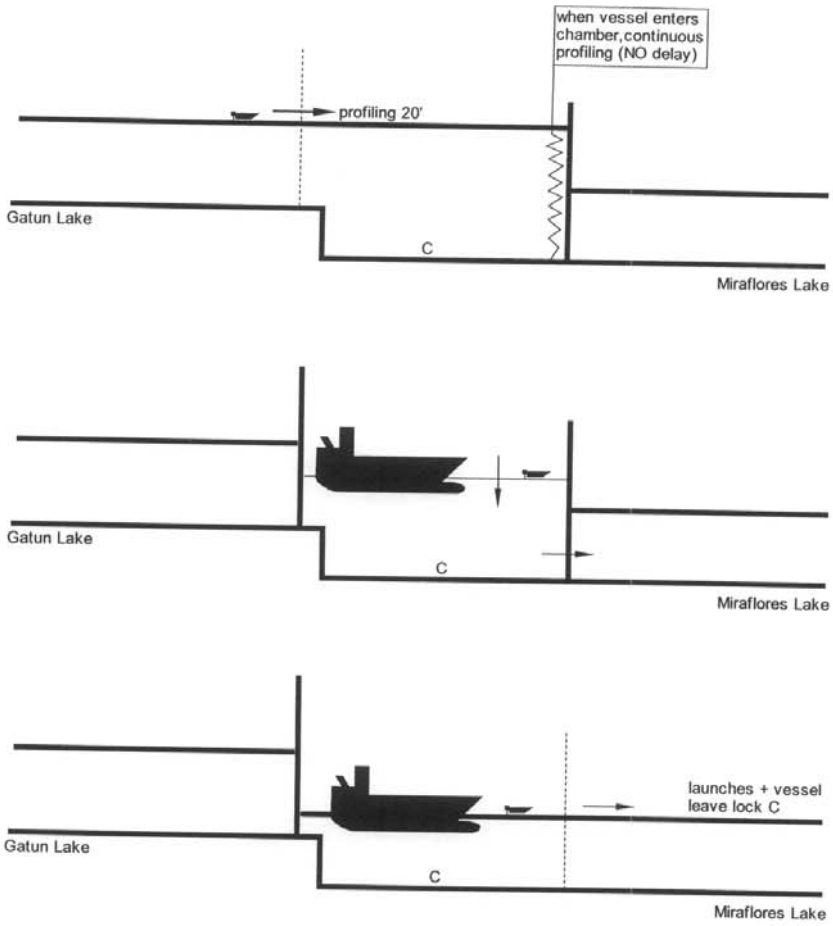
A-1-1



Pedro Miguel Locks

MORNING - NORTHBOUND - AHEAD OF VESSEL

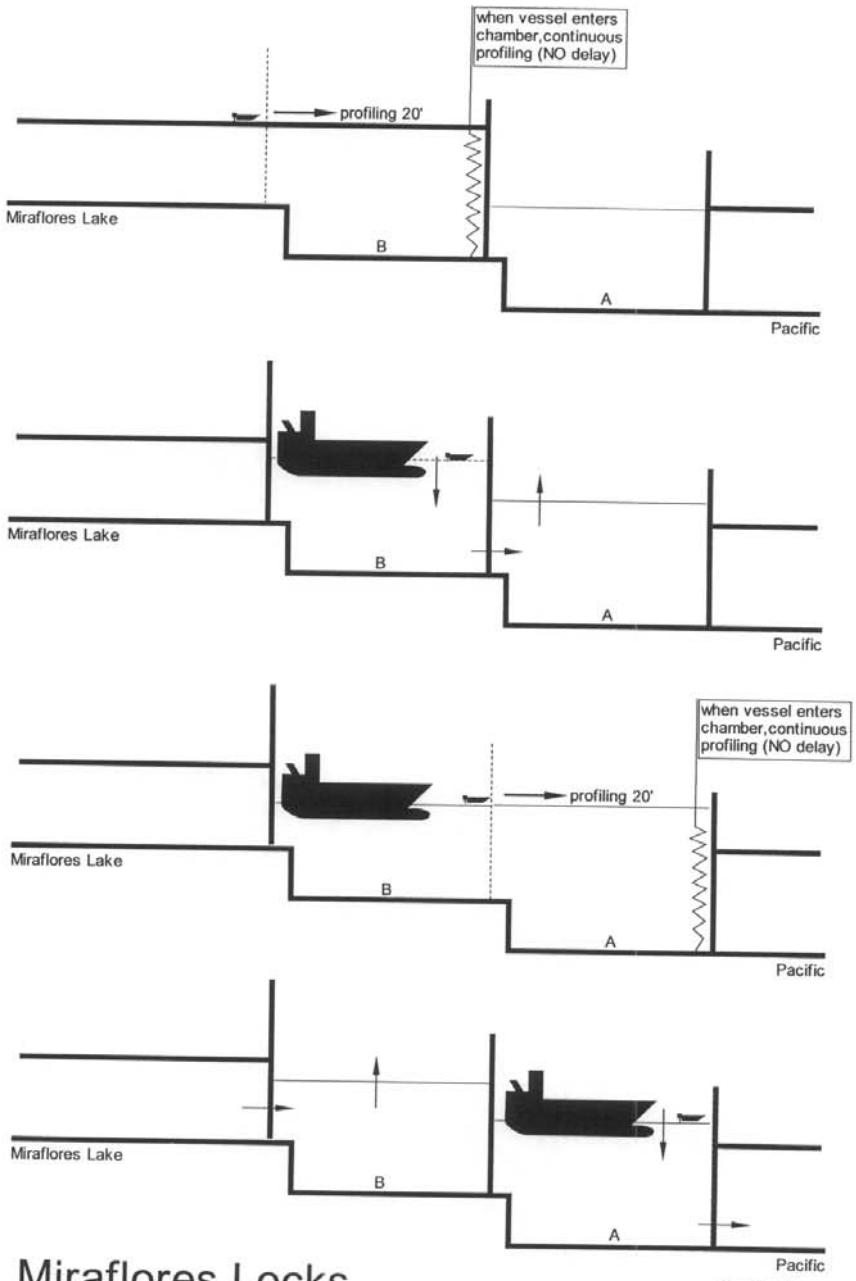
A-1-2



Pedro Miguel Locks

SOUTHBOUND - AHEAD OF VESSEL

A-2-1



Miraflores Locks

SOUTHBOUND - AHEAD OF VESSEL

A-2-2

Day B

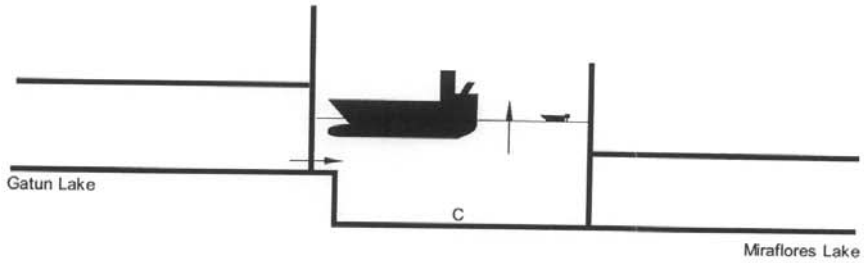
Morning northbound vessels. Start at downstream side of Pedro Migual locks. East lane or West lane.

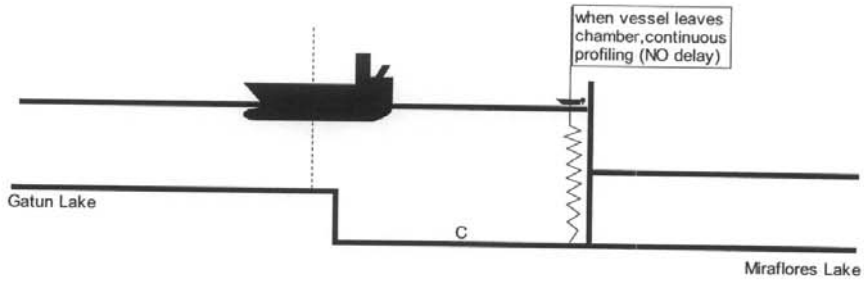
step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	C		astern of vessel in lock C	levelling		
2	C	high	astern of vessel in lock C	vessel leaves C profiling in C		x
3	C	high	in empty closed lock C	profiling in C max delay 20 min	x	
4	C		in empty closed lock C	levelling		
5	C	low	in empty closed lock C	profiling in C max delay 20 min	x	
6	C	low	in empty open lock C	launches leave lock C		
7	C			launches move to upstream side		

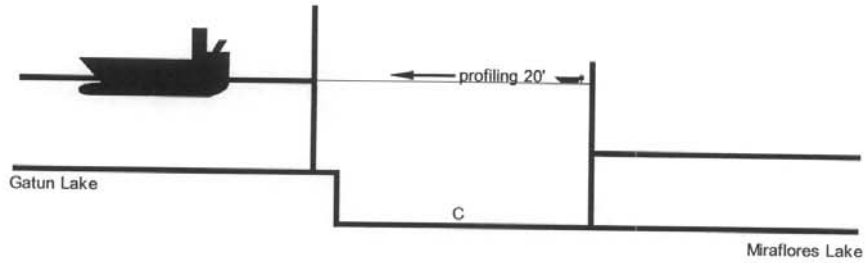
Afternoon southbound vessels. Start at upstream side of Pedro Miguel locks. East lane or West lane.

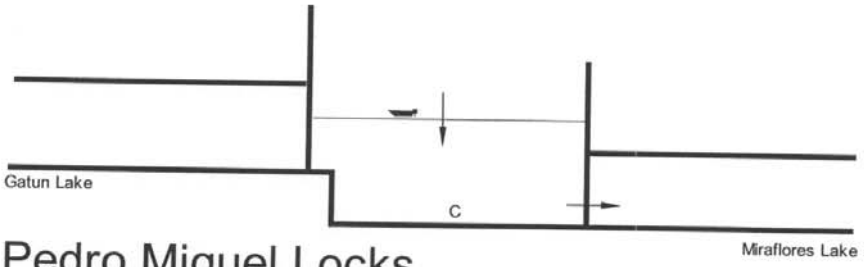
step	lock	water level in lock	position of launches	activity	long sections	positions near gates
8	C		astern of vessel in lock C	levelling		
9	C	low	astern of vessel in lock C	vessel leaves C profiling in C		x
10	C	low	in empty closed lock C	profiling in C max delay 20 min	x	
11	C		in empty closed lock C	levelling		
12	C	high	in empty closed lock C	profiling in C max delay 20 min	x	
13	C		ahead of vessel in lock C	levelling		
14	C	low	ahead of vessel	launches + vessel leave lock C		

Remark: after step 12 launches may leave lock C and remain at upstream side of Pedro Miguel locks.





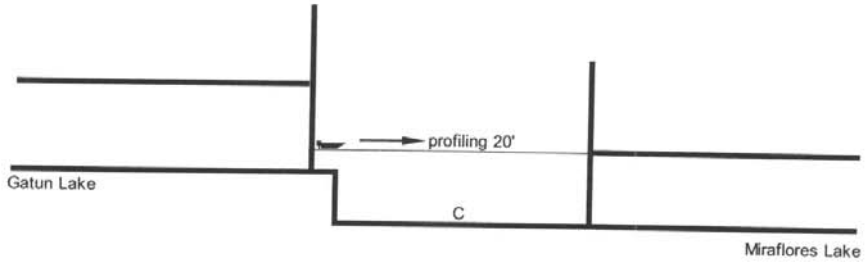


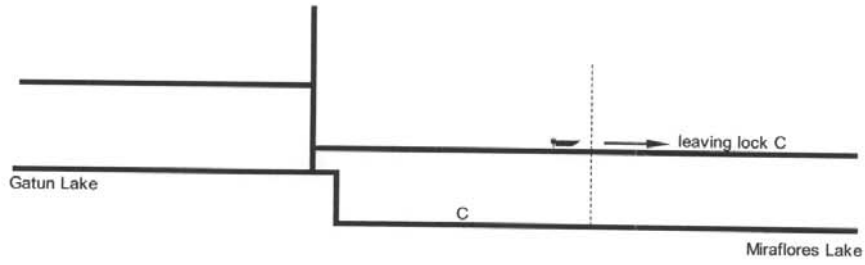


Pedro Miguel Locks

MORNING - NORTHBOUND - BEHIND VESSEL

B-1-1

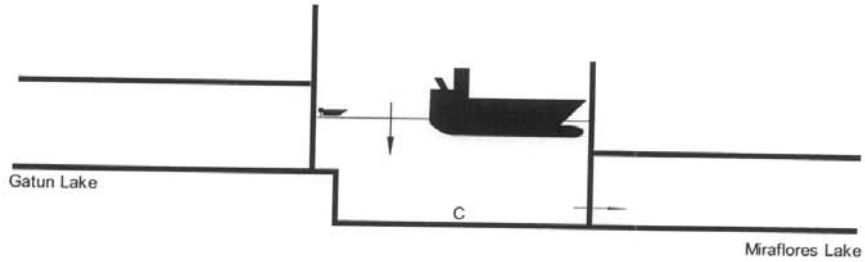


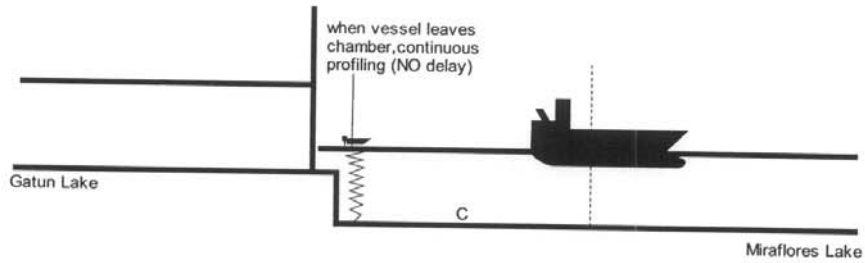


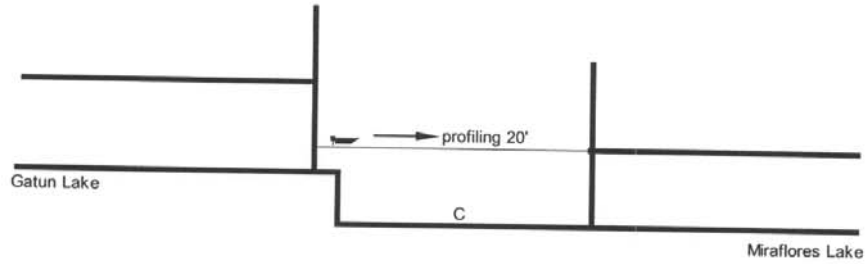
Pedro Miguel Locks

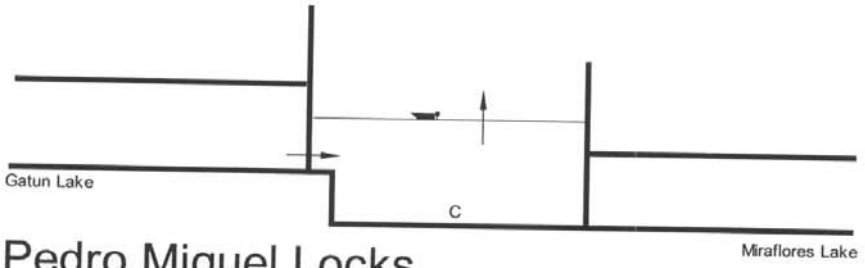
MORNING - NORTHBOUND - BEHIND VESSEL

B-1-2





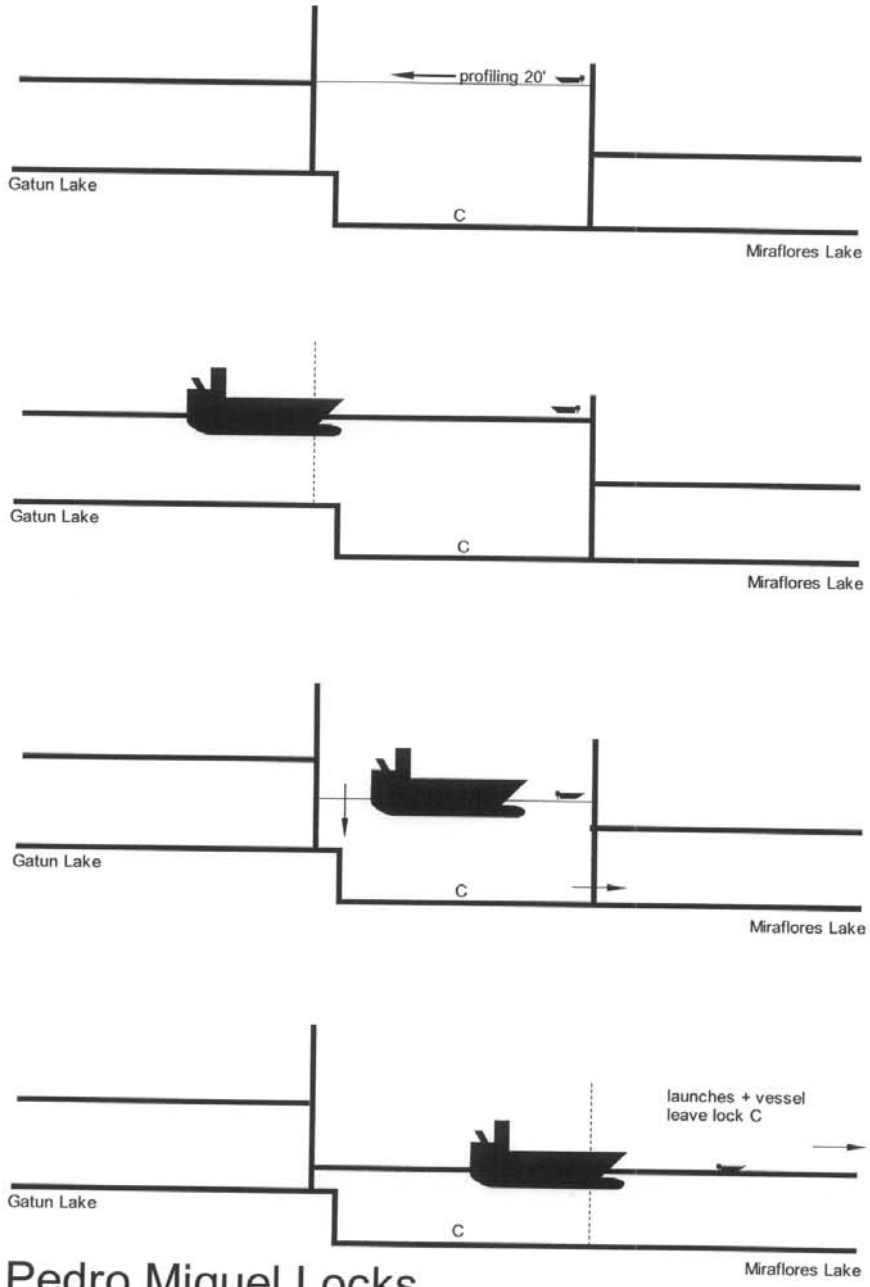




Pedro Miguel Locks

SOUTHBOUND - BEHIND VESSEL

B-2-1



Pedro Miguel Locks

SOUTHBOUND - BEHIND VESSEL

B-2-2

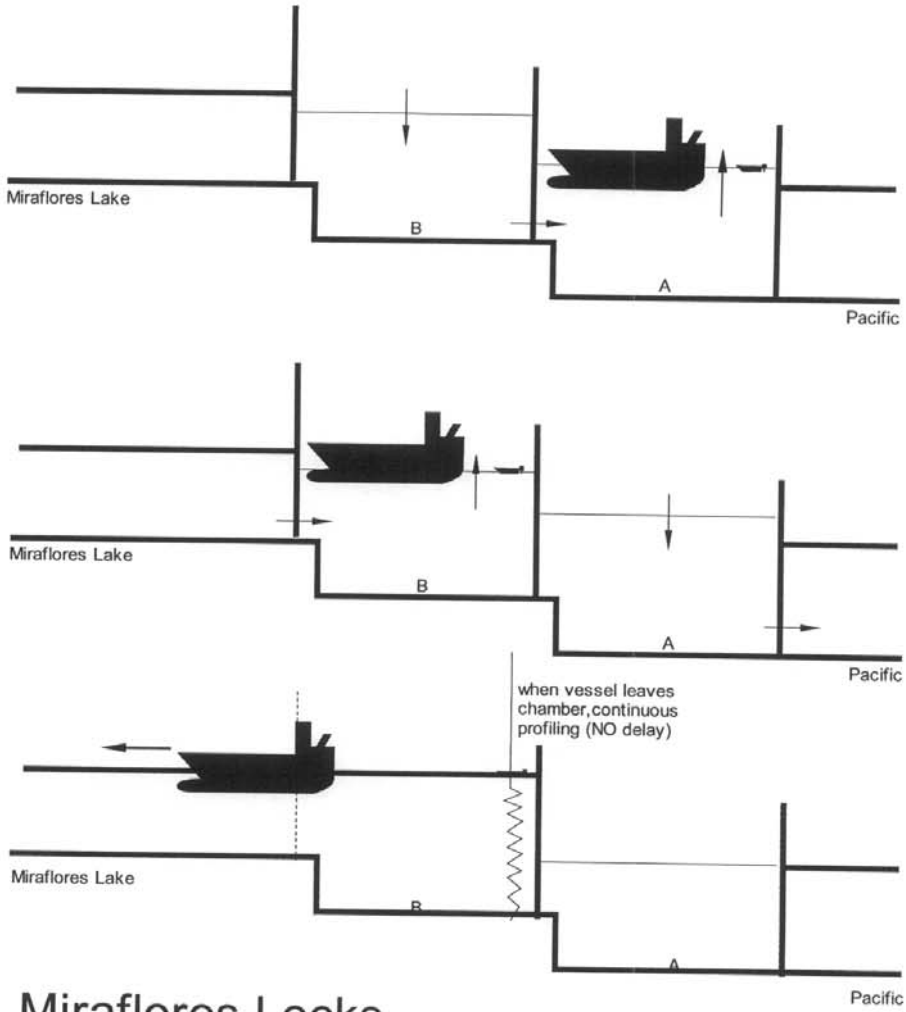
Day C

Morning northbound vessels. Start at downstream side of Miraflores locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	A		astern of vessel in lock A	levelling		
2	B		astern of vessel in lock B	levelling		
3	B	high	astern of vessel in lock B	vessel leaves B profiling in B		x
4	B	high	in empty closed lock B	profiling in B max delay 20 min	x	
5	B		in empty closed lock B	levelling		
6	B	low	in empty closed lock B	profiling in B max delay 20 min	x	
7	B		ahead of vessel in lock B	levelling		
8	B	high	ahead of vessel	launches + vessel leave lock B		

Afternoon southbound vessels. Start at upstream side of Miraflores locks. East lane or West lane.

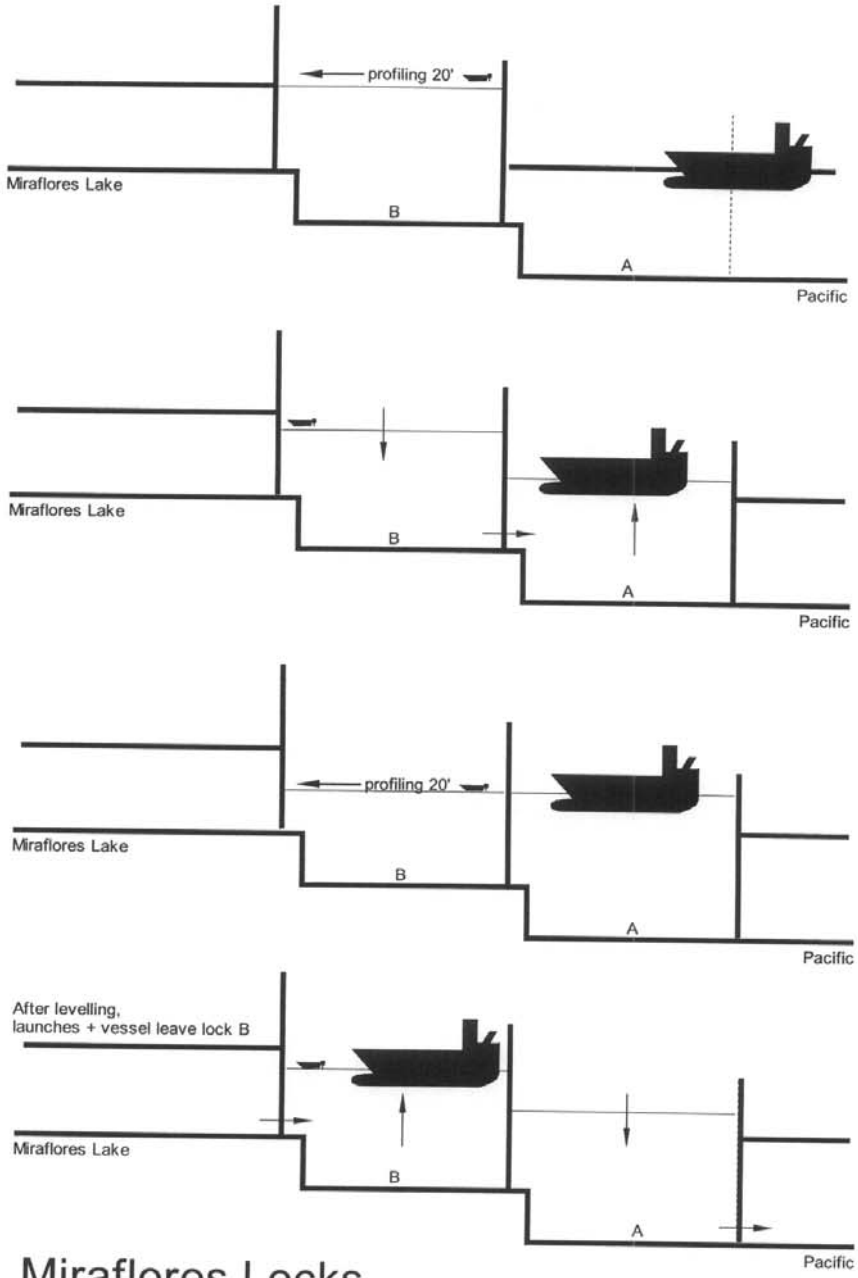
step	lock	water level in lock	position of launches	activity	long sections	positions near gates
9	B		astern of vessel in lock B	levelling		
10	B	low	astern of vessel in lock B	vessel leaves B profiling in B		x
11	B	low	in empty closed lock B	profiling in B max delay 20 min	x	
12	B		in empty closed lock B	levelling		
13	B	high	in empty closed lock B	profiling in B max delay 20 min	x	
14	B		ahead of vessel in lock B	levelling		
15	A		ahead of vessel in lock A	levelling		
16	A	low	ahead of vessel	launches + vessel leave lock A		



Miraflores Locks

MORNING - NORTHBOUND - BEHIND VESSEL

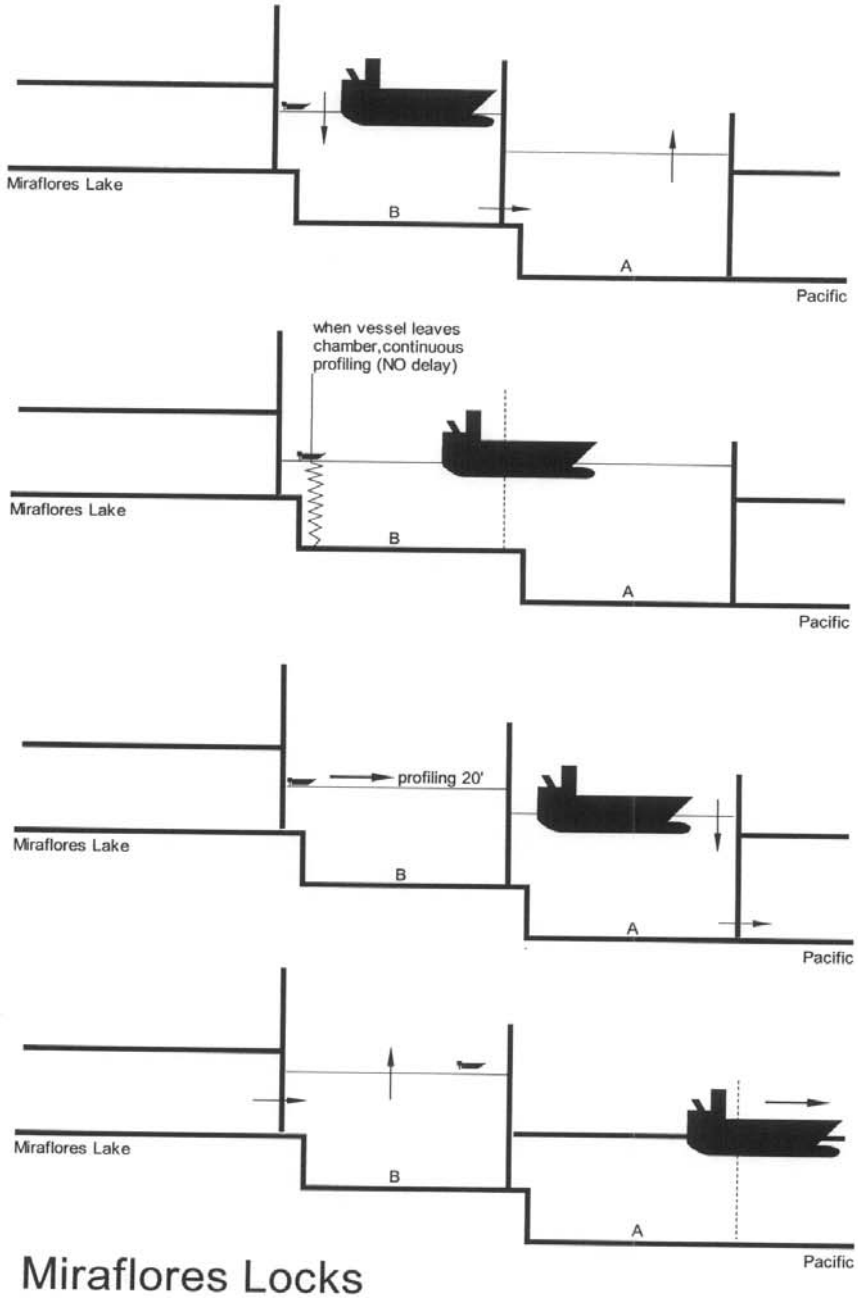
C-1-1



Miraflores Locks

MORNING - NORTHBOUND - BEHIND VESSEL

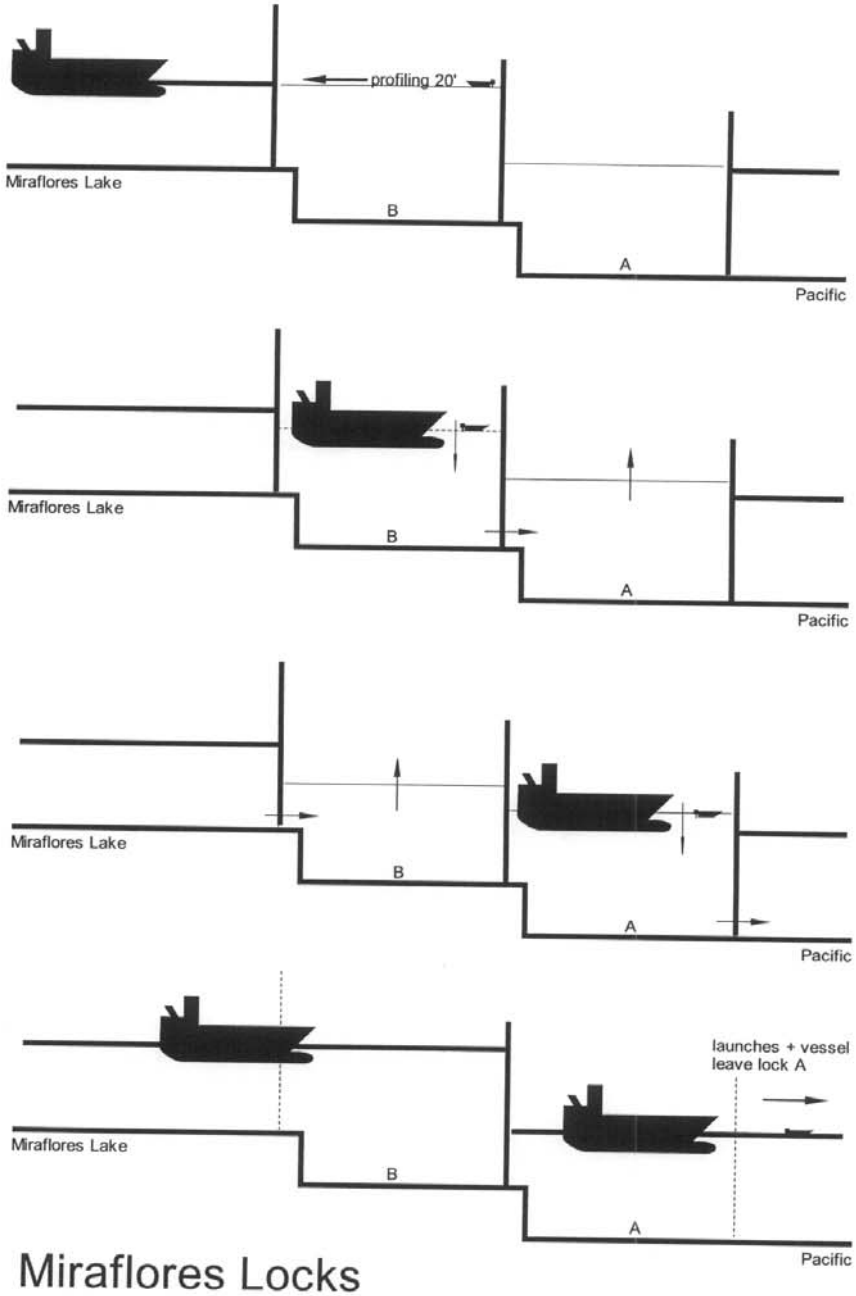
C-1-2



Miraflores Locks

SOUTHBOUND - BEHIND VESSEL

C-2-1



Miraflores Locks

SOUTHBOUND - BEHIND VESSEL

C-2-2

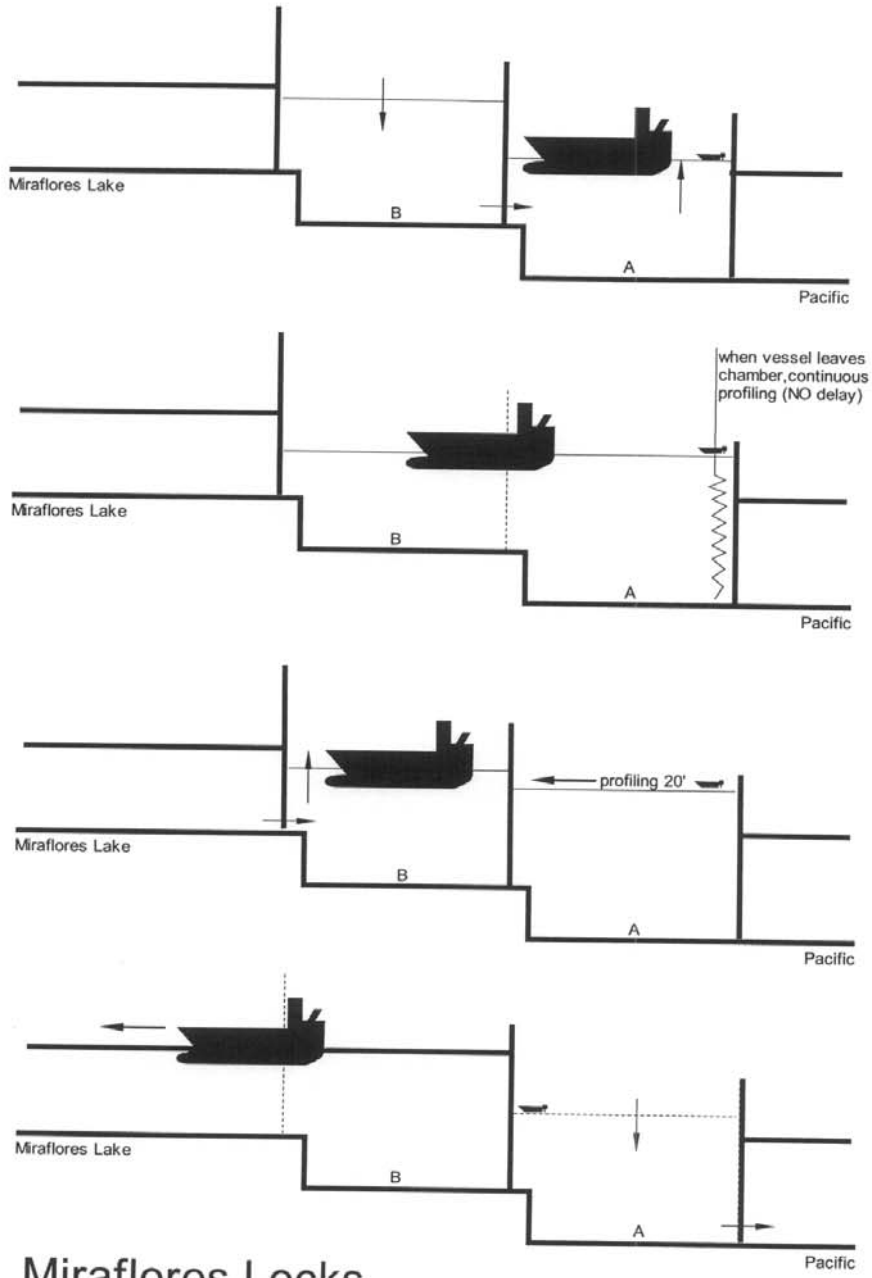
Day D

Pacific Ocean: high tide
Morning northbound vessels. Start at downstream side of Miraflores locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	A		astern of vessel in lock A	levelling		
2	A	high	astern of vessel in lock A	vessel leaves A profiling in A		x
3	A	high	in empty closed lock A	profiling in A max delay 20 min	x	
4	A		in empty closed lock A	levelling		
5	A	low	in empty closed lock A	profiling in A max delay 20 min	x	
6	A		ahead of vessel in lock A	levelling		
7	B		ahead of vessel in lock B	levelling		
8	B	high	ahead of vessel	launches + vessel leave lock B		

Pacific Ocean: low tide
Afternoon southbound vessels. Start at upstream side of Miraflores locks. East lane or West lane.

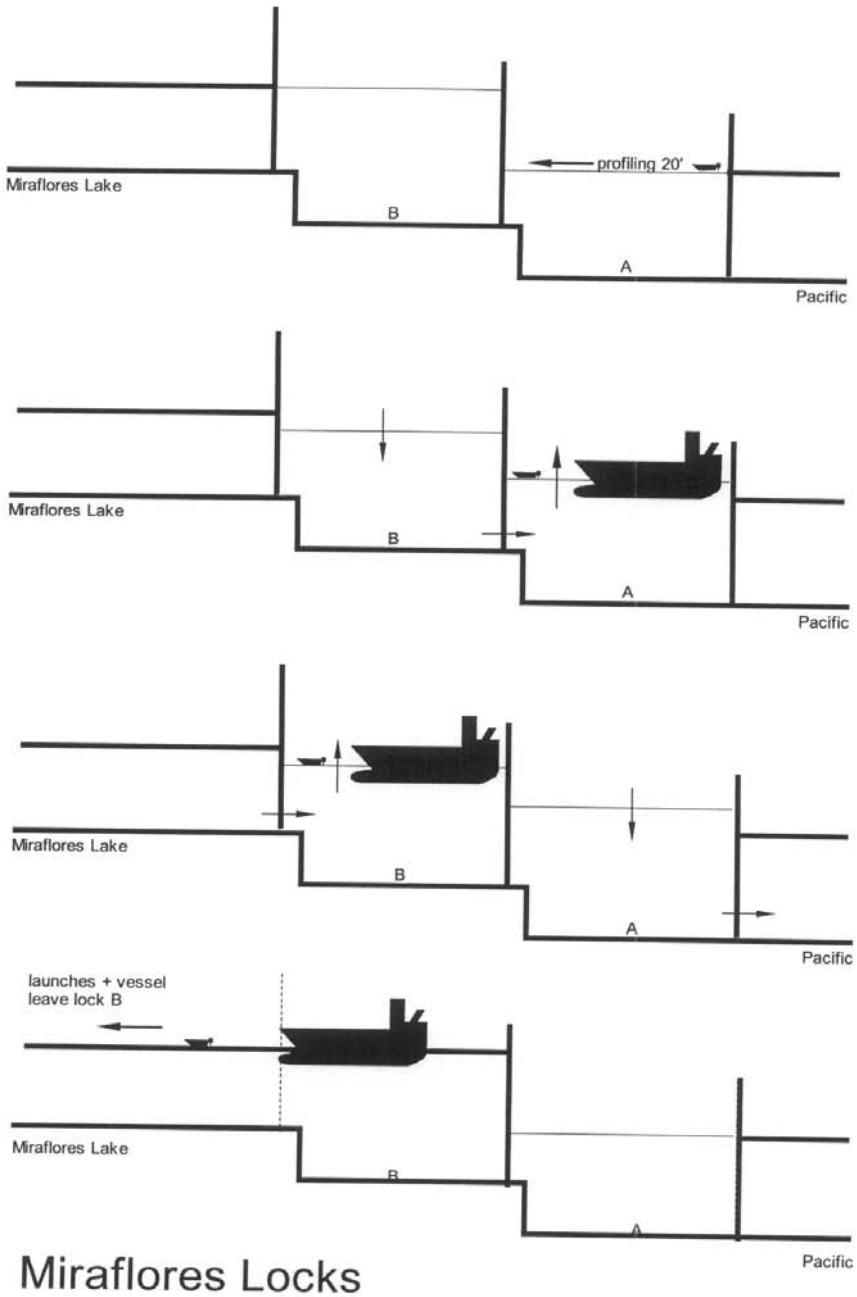
step	lock	water level in lock	position of launches	activity	long sections	positions near gates
9	B		astern of vessel in lock B	levelling		
10	A		astern of vessel in lock A	levelling		
11	A	low	astern of vessel in lock A	vessel leaves A profiling in A		x
12	A	low	in empty closed lock A	profiling in A max delay 20 min	x	
13	A		in empty closed lock A	levelling		
14	A	high	in empty closed lock A	profiling in A max delay 20 min	x	
15	A		ahead of vessel in lock A	levelling		
16	A	low	ahead of vessel	launches + vessel leave lock A		



Miraflores Locks

MORNING - NORTHBOUND - BEHIND VESSEL

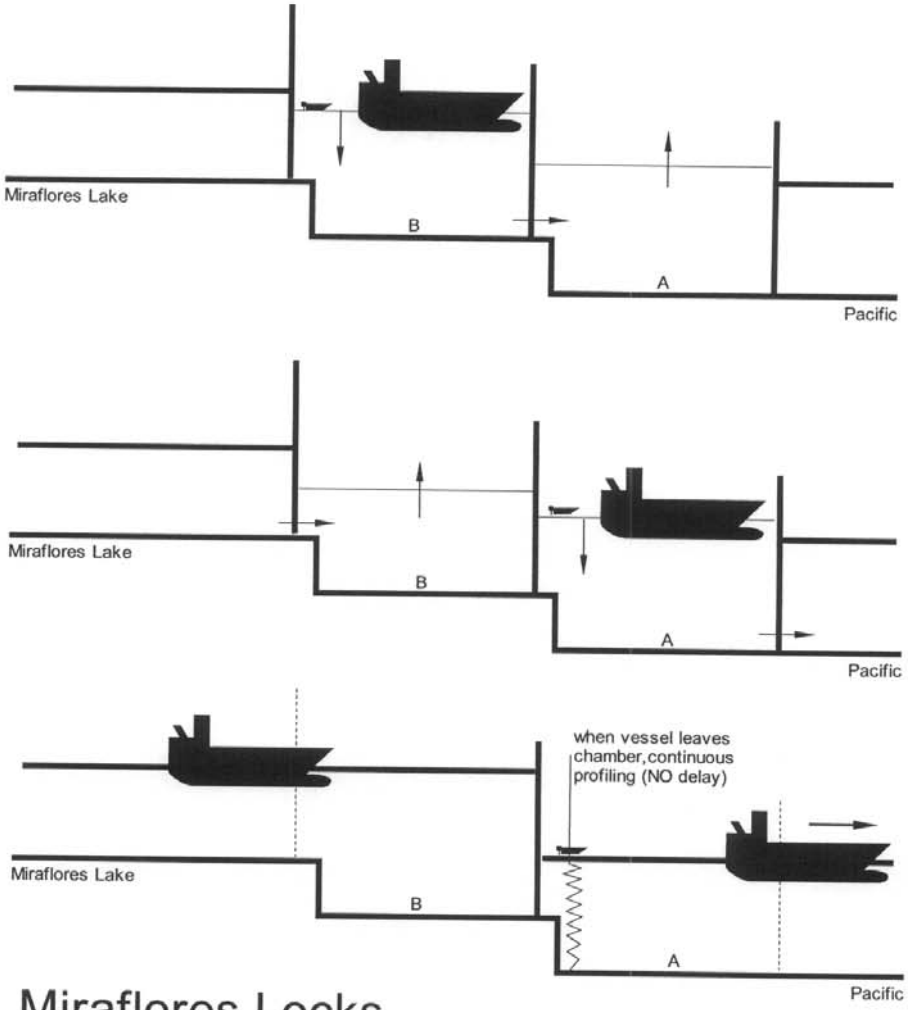
D-1-1



Miraflores Locks

MORNING - NORTHBOUND - BEHIND VESSEL

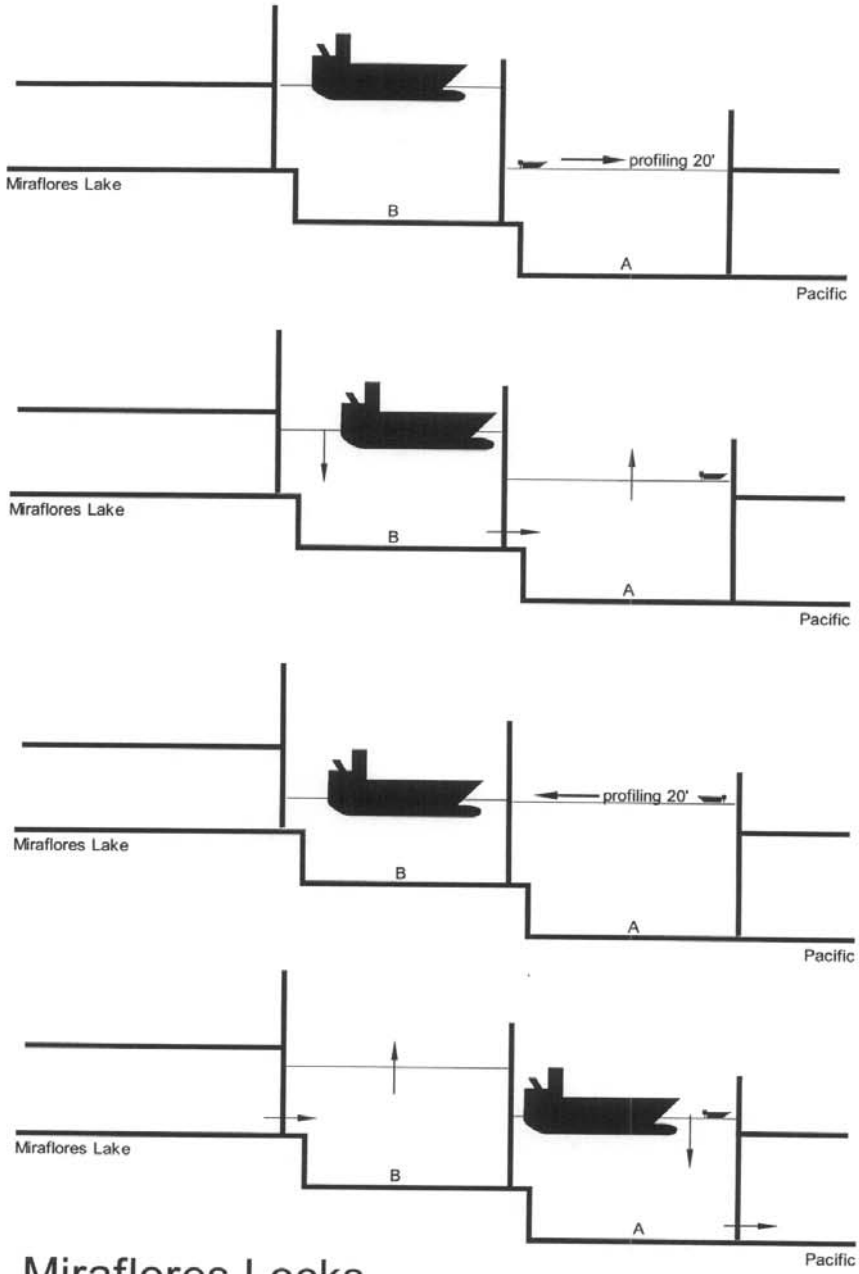
D-1-2



Miraflores Locks

SOUTHBOUND - BEHIND VESSEL

D-2-1



Miraflores Locks

SOUTHBOUND - BEHIND VESSEL

D-2-2

after levelling, vessel + launches leave lock A

Day E

Pacific Ocean: low tide
Morning northbound vessels. Start at downstream side of Miraflores locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	A		astern of vessel in lock A	levelling		
2	A	high	astern of vessel in lock A	vessel leaves A profiling in A		x
3	A	high	in empty closed lock A	profiling in A max delay 20 min	x	
4	A		in empty closed lock A	levelling		
5	A	low	in empty closed lock A	profiling in A max delay 20 min	x	
6	A		ahead of vessel in lock A	levelling		
7	B		ahead of vessel in lock B	levelling		
8	B	high	ahead of vessel	launches + vessel leave lock B		

Pacific Ocean: high tide
Afternoon southbound vessels. Start at upstream side of Miraflores locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
9	B		astern of vessel in lock B	levelling		
10	A		astern of vessel in lock A	levelling		
11	A	low	astern of vessel in lock A	vessel leaves A profiling in A		x
12	A	low	in empty closed lock A	profiling in A max delay 20 min	x	
13	A		in empty closed lock A	levelling		
14	A	high	in empty closed lock A	profiling in A max delay 20 min	x	
15	A		ahead of vessel in lock A	levelling		
16	A	low	ahead of vessel	launches + vessel leave lock A		

3.3 Measurements in Gatun Locks

Measurements will take place on four, non-consecutive days, referred to as day F – day I. These days can independently be planned in the transit schedule. The tide difference at the Atlantic side is relatively small and is not taken into account in the set up of the measurement programme. The various steps in the programme is shown on the next pages.

Day F

Morning southbound vessels. Start at downstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	D	low	in lock D; vessel waits	profiling in D max delay 20 min	x	x
2	D		ahead of vessel in lock D	levelling		
3	E	low	in lock E; vessel waits in D	profiling in E max delay 20 min	x	x
4	E		ahead of vessel in lock E	levelling		
5	F	low	in lock F; vessel waits in E	profiling in F max delay 20 min	x	x
6	F		ahead of vessel in lock F	levelling		
7	F	high	ahead of vessel	launches + vessel leave lock F		

Afternoon northbound vessels. Start at upstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
8	F	high	in lock F; vessel waits	profiling in F max delay 20 min	x	x
9	F		ahead of vessel in lock F	levelling		
10	E	high	in lock E; vessel waits in F	profiling in E max delay 20 min	x	x
11	E		ahead of vessel in lock E	levelling		
12	D	high	in lock D; vessel waits in E	profiling in D max delay 20 min	x	x
13	D		ahead of vessel in lock D	levelling		
14	D	low	ahead of vessel	launches + vessel leave lock D		

Day G

Morning southbound vessels. Start at downstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	D		astern of vessel in lock D	levelling		
2	D	high	astern of vessel in lock D	vessel leaves D profiling in D		x
3	D	high	in empty closed lock D	profiling in D max delay 20 min	x	
4	D		in empty closed lock D	levelling		
5	D	low	in empty closed lock D	profiling in D max delay 20 min	x	
6	D		ahead of vessel in lock D	levelling		
7	E		ahead of vessel in lock E	levelling		
8	F		ahead of vessel in lock F	levelling		
9	F	high	ahead of vessel	launches + vessel leave lock F		

Afternoon northbound vessels. Start at upstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
10	F		astern of vessel in lock F	levelling		
11	F	low	astern of vessel in lock F	vessel leaves F profiling in F		x
12	F	low	in empty closed lock F	profiling in F max delay 20 min	x	
13	F		in empty closed lock F	levelling		
14	F	high	in empty closed lock F	profiling in F max delay 20 min	x	
15	F		ahead of vessel in lock F	levelling		
16	E		ahead of vessel in lock E	levelling		
17	D		ahead of vessel in lock D	levelling		
18	D	low	ahead of vessel	launches + vessel leave lock D		

Day H

Morning southbound vessels. Start at downstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	D		astern of vessel in lock D	levelling		
2	E		astern of vessel in lock E	levelling		
3	E	high	astern of vessel in lock E	vessel leaves E profiling in E		x
4	E	high	in empty closed lock E	profiling in E max delay 20 min	x	
5	E		in empty closed lock E	levelling		
6	E	low	in empty closed lock E	profiling in E max delay 20 min	x	
7	E		ahead of vessel in lock E	levelling		
8	F		ahead of vessel in lock F	levelling		
9	F	high	ahead of vessel	launches + vessel leave lock F		

Afternoon northbound vessels. Start at upstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
10	F		astern of vessel in lock F	levelling		
11	E		astern of vessel in lock E	levelling		
12	E	low	astern of vessel in lock E	vessel leaves E profiling in E		x
13	E	low	in empty closed lock E	profiling in E max delay 20 min	x	
14	E		in empty closed lock E	levelling		
15	E	high	in empty closed lock E	profiling in E max delay 20 min	x	
16	E		ahead of vessel in lock E	levelling		
17	D		ahead of vessel in lock D	levelling		
18	D	low	ahead of vessel	launches + vessel leave lock D		

Day I

Morning southbound vessels. Start at downstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
1	D		astern of vessel in lock D	levelling		
2	E		astern of vessel in lock E	levelling		
3	F		astern of vessel in lock F	levelling		
4	F	high	astern of vessel in lock F	vessel leaves F profiling in F		x
5	F	high	in empty closed lock F	profiling in F max delay 20 min	x	
6	F		in empty closed lock F	levelling		
7	F	low	in empty closed lock F	profiling in F max delay 20 min	x	
8	F		ahead of vessel in lock F	levelling		
9	F	high	ahead of vessel	launches + vessel leave lock F		

Afternoon northbound vessels. Start at upstream side of Gatun locks. East lane or West lane.

step	lock	water level in lock	position of launches	activity	long sections	positions near gates
10	F		astern of vessel in lock F	levelling		
11	E		astern of vessel in lock E	levelling		
12	D		astern of vessel in lock D	levelling		
13	D	low	astern of vessel in lock D	vessel leaves D profiling in D		x
14	D	low	in empty closed lock D	profiling in D max delay 20 min	x	
15	D		in empty closed lock D	levelling		
16	D	high	in empty closed lock D	profiling in D max delay 20 min	x	
17	D		ahead of vessel in lock D	levelling		
18	D	low	ahead of vessel	launches + vessel leave lock D		

Appendix II

Dry Season Data Collection Programme

(Version dated March 2002)

1 Introduction

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 no SAA-74337). The services of WL | Delft are subdivided in eight major work tasks (see Detailed Project Workplan and Schedule, October 2001). Part of work task 2 is the set up of a programme for data collection on salinity levels and salt water intrusion through the locks in the dry season. This data-collection programme is presented in the present report. The dry-season measurements are scheduled for April 2002, weeks 15 and 16, at the end of the dry season, when the water level in Gatun Lake is low.

The aim of the measurements in the dry season is:

To measure salinity levels in Miraflores Lake, Gaillard Cut and Gatun Lake at selected locations and, by comparing with the previous measurements, to get insight in changes in salinity levels after a period of little rainfall.
To broaden the insight in the hydraulic processes which occur in the locks during operation, by means of additional salinity measurements in forebays and lock chambers.
To fill up gaps in measurement data of the wet-season programme, in particular gaps in measurement data for locks at the Pacific side, both under low tide and high tide conditions.

The dry-season measurement programme has been set up taking into account the experiences and insights which have been obtained through the wet-season measurements in weeks 48 – 50, 2001.

Chapter 2 presents an explanation of the salinity measurements in the locks in the wet season during five different phases in the locking process, both for uplockage and downlockage. Also additional measurements in the forebays of the locks during three different stages of the locking process are explained; these measurements will be executed in the coming measurement campaign.

Exchange coefficients are derived from the salinity measurements in locks and forebays. Missing information is indicated; this data will be collected through the dry-season measurement programme.

The dry-season measurement programme is presented in Chapter 4.

2 Measurements in locks and forebays

Salinity measurements in lock chambers
In lock operation two steps in particular can be distinguished, which are relevant for the salt water intrusion process. These steps are described here in brief, both for uplockage and downlockage.

Uplockage

Step 1: gates are opened and the ship moves from low basin to high basin
The low basin can either be sea entrance, lock or lake. In the case of sea entrance and lake there is no upward step in the floor at the entrance to the high basin. The high basin can either be lock or lake.
When the gates between low and high basin are opened density-driven exchange flows occur. These flows depend on density difference between the two basins, local geometry, position of the vessel, and duration of gate opening. When the ship moves from basin to basin the ship's submerged volume is exchanged. The propellor of the ship causes mixing.
Step 1 is finished when the gates between both basins have been closed.

Step 2: equalize water level in low basin (with ship) with water level in high basin (without ship)
The low basin can either be lock or lake. In the case of lake the water level in the low basin remains almost the same and the high basin (lock) is levelled down. The high basin can either be lock or lake. When low and high basin are locks the initial water level difference between the basins is highest as well as initial jet flow velocities.
Fill water is drawn from the higher basin. When the high basin is a lock water is drawn through distributed openings in the floor; when the high basin is a lake water is drawn through a few openings in centre wall and / or side wall. Mixing in the low basin depends on inflow velocity, double or single-culvert lockage and ship dimensions.
Step 2 is finished when the gates between both basins are pressed open by the water in the low basin (in the case of a density difference between the basins the water level in the high basin is still a little above the water level in the low basin).

For practical reasons it is not possible to continuously measure the salinity levels and changes of salinity throughout the lock chambers during the full uplockage process. Measurements, therefore, are limited to a few phases of the lockage process. These phases are:

Measurement of salinity profiles in long sections in the lock chamber prior to entering of the ship.
Measurement of salinity profiles near the upstream gates when the ship moves in.
Measurement of salinity profiles near the downstream gates when the ship moves out.
Measurement of salinity profiles in long sections in the lock chamber after the ship has left and the gates are closed.
Measurement of salinity profiles in long sections in the lock chamber after the water has levelled down and prior to opening of the downstream gates.

The five different phases are shown in next figure.

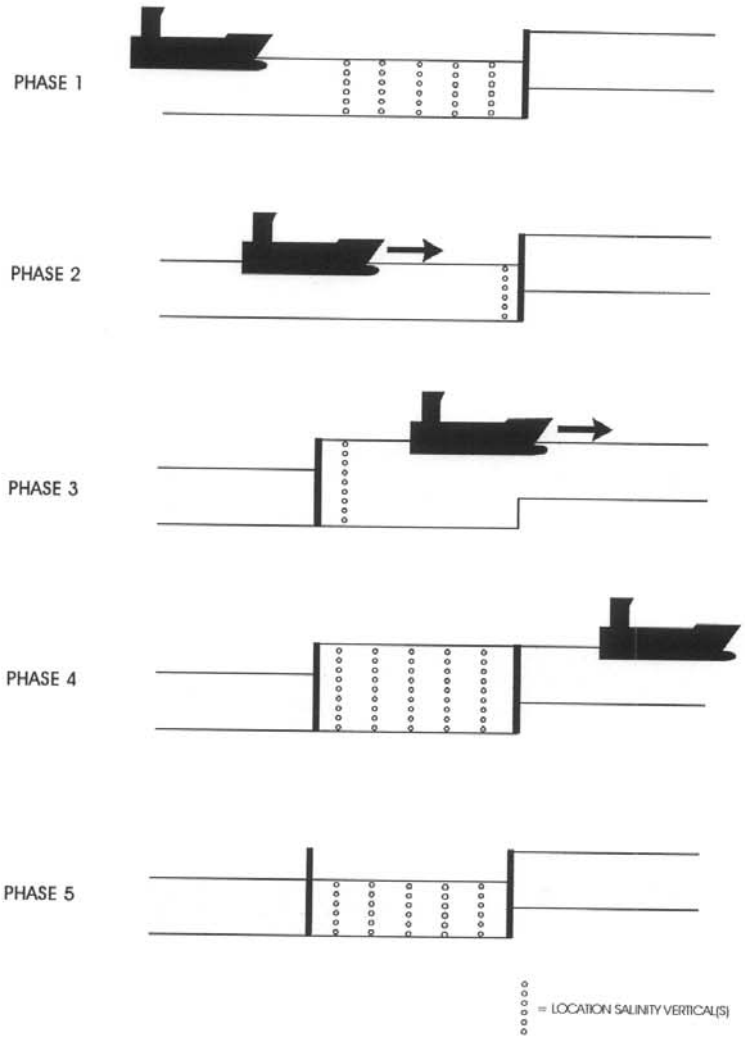


Figure 2.1 Measurements in lock chambers during uplockage

Downlockage

Step 1: gates are opened and the ship moves from high basin to low basin
The high basin can either be lake or lock. The low basin can either be lake, lock or sea entrance. In the case of lake and sea entrance there is no downward step in the floor at the entrance to the low basin.
When the gates between high and low basin are opened density-driven exchange flows occur. These flows depend on density difference between the two basins, local geometry, position of the vessel, and duration of gate opening. When the ship moves from basin to basin the ship's submerged volume is exchanged. The propellor of the ship causes mixing.
Step 1 is finished when the gates between both basins have been closed.

Step 2: equalize water level in low basin (without ship) with water level in high basin (with ship)
The high basin can either be lake or lock. In the case of lake the water level in the high basin remains almost the same and the low basin (lock) is levelled up. The low basin can either be lake, lock or sea entrance. When high and low basin are locks the initial water level difference between the basins is highest as well as initial jet flow velocities.
Fill water is drawn from the higher basin. When the high basin is a lake water is drawn through a few openings in centre wall and / or side wall; when the high basin is a lock water is drawn through distributed openings in the floor; the ship is above these openings. Mixing in the low basin depends on inflow velocity and double or single-culvert lockage.
Step 2 is finished when the gates between both basins are pressed open by the water in the low basin (in the case of a density difference between the basins the water level in the high basin is still a little above the water level in the low basin).

For downlockage similar measurement phases can be distinguished as for uplockage. These phases are:

Measurement of salinity profiles in long sections in the lock chamber prior to entering of the ship.
Measurement of salinity profiles near the downstream gates when the ship moves in.
Measurement of salinity profiles near the upstream gates when the ship moves out.
Measurement of salinity profiles in long sections in the lock chamber after the ship has left and the gates are closed.
Measurement of salinity profiles in long sections in the lock chamber after the water has levelled up and prior to opening of the upstream gates.

The five phases are shown in next figure.

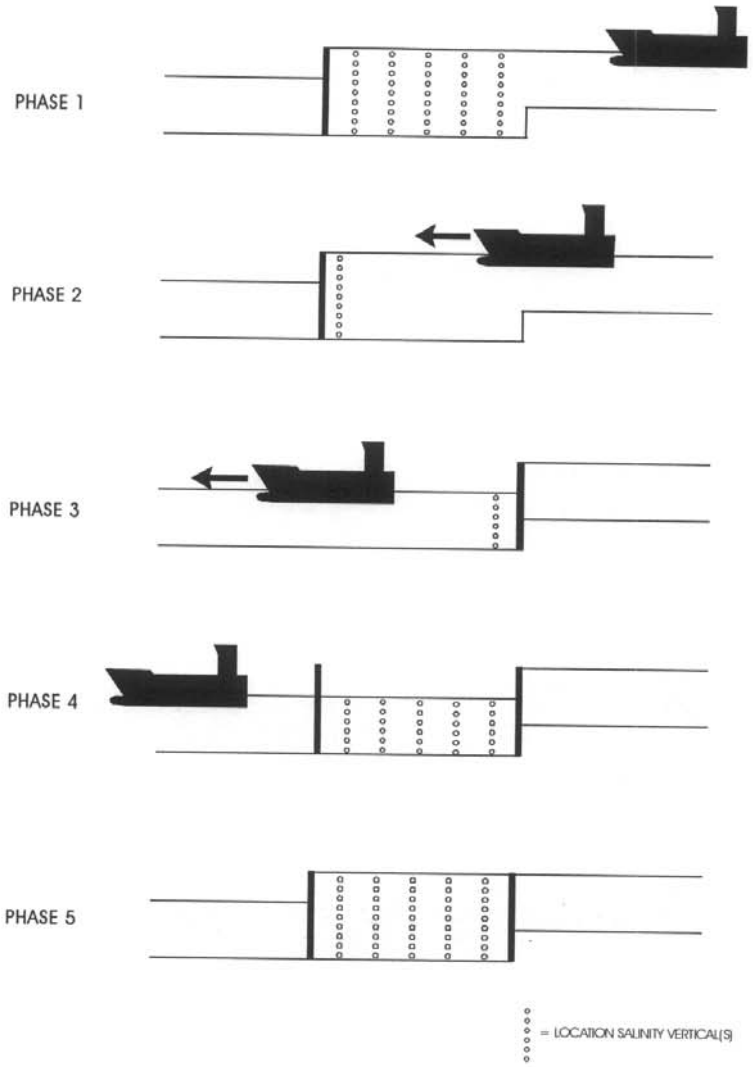


Figure 2.2 Measurements in lock chambers during downlockage

The data-collection programme for the wet season was set up in accordance with the above five-phases measurement scheme.

Salinity measurements in forebays

In order to complete the information that is relevant for the study of the salt water intrusion process through the locks on the Panama Canal salinity measurements are required in the forebays at upstream and downstream side of the locks (in addition to salinity measurements

in the lock chambers). Measurements are needed in three different stages of the lockage process:

Uplockage, forebay at downstream side of locks

a Measurement of the salinity level of water that is spilled from a lock to the forebay at the downstream side (salinity measurements from launches, which are positioned near the outlet of the side-wall culvert or centre-wall culvert). The forebay is either located in the Atlantic entrance, the Pacific entrance or in Miraflores Lake.
b Measurement of salinity profiles in long sections in the downstream-side forebay just after spilling and prior to opening of the lock gates and movement of the ship.
c Measurement of salinity profiles in long sections in the downstream-side forebay after passage of the ship and closure of the lock gates.

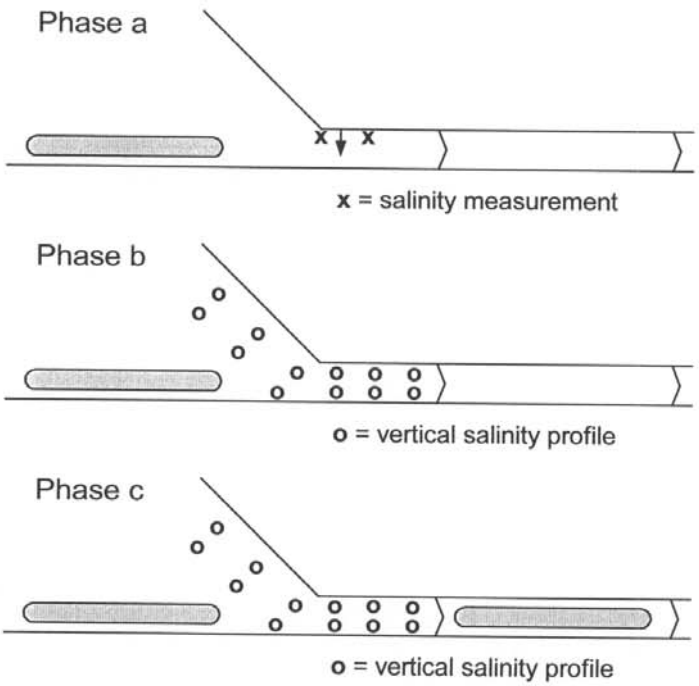


Figure 2.3 Uplockage; measurements in forebay, downstream side of locks

Uplockage, forebay at upstream side of locks

Salinity measurements are required during next three phases of the locking process:

a Measurement of the salinity level of water that is drawn from the upstream-side forebay of a lock (salinity measurements near the intake of the side-wall culvert or centre-wall culvert). The forebay is either located in Gatun Lake (Gaillard Cut) or in Miraflores Lake.

b Measurement of salinity profiles in long sections in the upstream-side forebay just after taking in of water and prior to opening of the lock gates and movement of the ship.
c Measurement of salinity profiles in long sections in the upstream-side forebay after passage of the ship and closure of the lock gates.

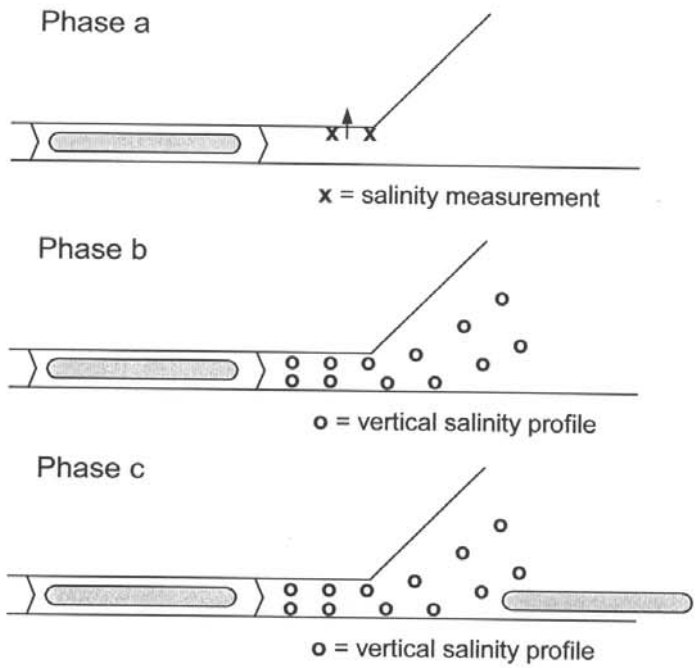


Figure 2.4 Uplockage; measurements in forebay, upstream side of locks

Downlockage, forebays at upstream and downstream sides of locks

Salinity measurements in the forebays at both sides of the locks during downlockage are required for the analysis of salt water intrusion. These measurements in three phases are similar as for uplockage, see Figures 2.5 and 2.6.

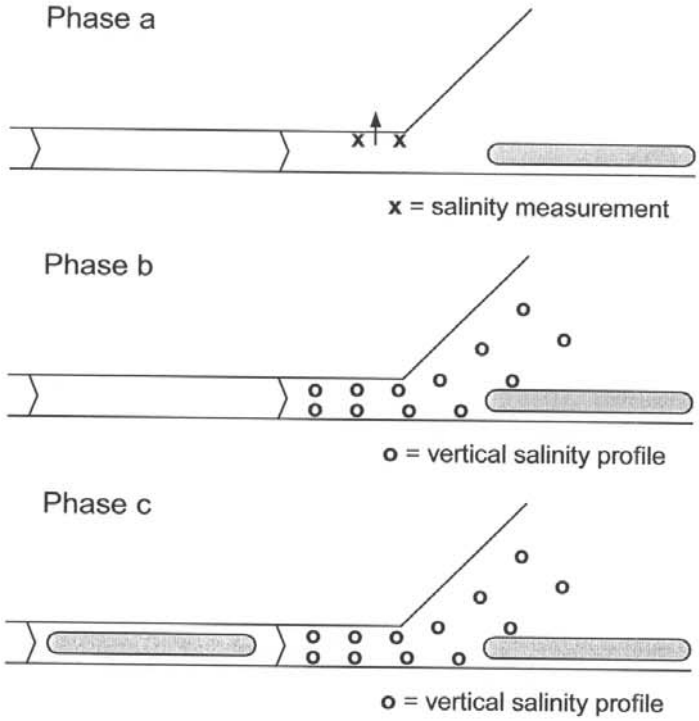


Figure 2.5 Downlockage; measurements in forebay, upstream side of locks

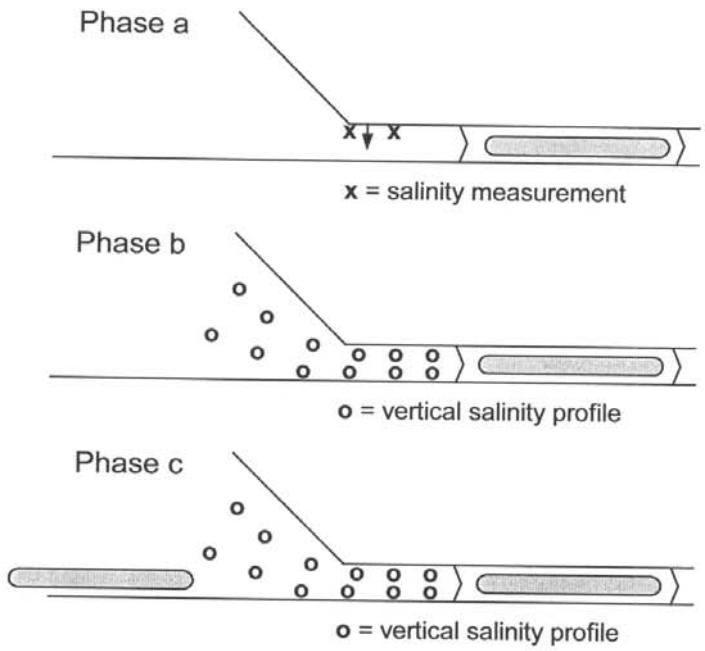


Figure 2.6 Downlockage; measurements in forebay, downstream side of locks

3 Determination of exchange coefficients

Exchange coefficients are used in the numerical model that simulates the salt water intrusion process through the locks on the Panama Canal. In the wet-season measurement campaign of November – December 2001 (weeks 48 – 50) we have collected data on salinity levels in the locks at the Atlantic and Pacific sides of the canal. The information obtained at the Pacific side, however, is not yet complete. This includes the effect of the great tidal variation at the Pacific side; the tidal variation requires more attention.
So far, only limited information is obtained on salinity levels in the forebays. In the next measurement campaign more data on salinity levels in all forebays (seaside and lake side) will be collected for different phases (see Section 2.2) of the locking process, both for uplockage and downlockage.
In the wet-season measurement campaign much data were collected on salinity levels in Gatun Lake, Gaillard Cut and Miraflores Lake. At the end of the dry season salinity levels in the lakes may have been changed; however, we expect that the number of profilings in the lakes can be considerably smaller than in the wet season and that measurements can be limited to areas near the upper locks, parts of the deep shipping lanes and near spillways.
No additional information is required on salinity levels in the seaside approach channels; in the previous measurement campaign data were collected in the entire channels up to the Bridge of the America's at the Pacific side and the protecting breakwaters at the Atlantic side. In the next campaign we will pay more attention to the variation of salinity levels in the seaside forebays of the lower locks.

The dry-season measurement campaign will focus on:

Salinity levels in Miraflores Lake, Gaillard Cut and Gatun Lake at some selected locations near the upper locks, in shipping lanes and near spillways.
Salinity levels in all forebays during various stages of the locking process; salinity levels in lock chambers during stages of the locking process in cases where information is missing or additional information is required.
The effect of tidal variation at the Pacific side on the salt water intrusion process.

Next tables present an overview of salinity measurements which are required to derive exchange coefficients for up- and downlockages. Text with gray background indicates that information has to be collected in the next measurement campaign.

UPLOCKAGE PACIFIC SIDE				
step	water movement or ship movement	measurements in high basin; phase	measurements in low basin; phase	remarks
1	water; A → forebay seaside	A; phase 4 and 5 phase 4	forebay seaside; - phase a	at high tide
1	water; A → forebay seaside	A; phase 4 and 5 phase 4	forebay seaside; - phase a	at low tide
2	ship; forebay seaside → A	A; phase 2 and 5 phase 5	forebay seaside; phase b phase b and c	at high tide
2	ship; forebay seaside → A	A; phase 2 and 5 phase 5	forebay seaside; phase b phase b and c	at low tide
1	water; B → A	B; phase 4 and 5 phase 4	A; - phase 2 and 3	
2	ship; A → B	B; phase 2 and 5 phase 5	A; phase 3 phase 3 and 4	
1	water; Miraflores Lake → B	forebay ML-south; phase a and c phase c	B; - phase 2 and 3	
2	ship; B → Miraflores Lake	forebay ML-south; phase b and c phase b	B; phase 3 phase 3 and 4	
1	water; C → Miraflores Lake	C; phase 4 and 5 phase 4	forebay ML-north; - phase a	
2	ship; Miraflores Lake → C	C; phase 2 and 5 phase 5	forebay ML-north; phase b phase b and c	
1	water; Gaillard Cut → C	forebay GC; phase a and c phase c	C; - phase 2 and 3	
2	ship; C → Gaillard Cut	forebay GC; phase b and c phase b	C; phase 3 phase 3 and 4	

DOWNLOCKAGE PACIFIC SIDE				
step	water movement or ship movement	measurements in high basin; phase	measurements in low basin; phase	remarks
1	water; A → forebay seaside	A; phase 2 and 3 phase 2	forebay seaside; - phase a	at high tide
1	water; A → forebay seaside	A; phase 2 and 3 phase 2	forebay seaside; - phase a	at low tide
2	ship; A → forebay seaside	A; phase 3 and 4 phase 3	forebay seaside; phase b phase b and c	at high tide
2	ship; A → forebay seaside	A; phase 3 and 4 phase 3	forebay seaside; phase b phase b and c	at low tide
1	water; B → A	B; phase 2 and 3 phase 2	A; - phase 4 and 5	
2	ship; B → A	B; phase 3 and 4 phase 3	A; phase 5 phase 2 and 5	
1	water; Miraflores Lake → B	forebay ML-south; phase a and c phase c	B; - phase 4 and 5	
2	ship; Miraflores Lake → B	forebay ML-south; phase b and c phase b	B; phase 5 phase 2 and 5	
1	water; C → Miraflores Lake	C; phase 2 and 3 phase 2	forebay ML-north; - phase a	
2	ship; C → Miraflores Lake	C; phase 3 and 4 phase 3	forebay ML-north; phase b phase b and c	
1	water; Gaillard Cut → C	forebay GC; phase a and c phase c	C; - phase 4 and 5	
2	ship; Gaillard Cut → C	forebay GC; phase b and c phase b	C; phase 5 phase 2 and 5	

UPLOCKAGE ATLANTIC SIDE				
step	water movement or ship movement	measurements in high basin; phase	measurements in low basin; phase	remarks
1	water; D → forebay seaside	D; phase 4 and 5 phase 4	forebay seaside; - phase a	negligible tidal influence
2	ship; forebay seaside → D	D; phase 2 and 5 phase 5	forebay seaside; phase b phase b and c	negligible tidal influence
1	water; E → D	E; phase 4 and 5 phase 4	D; - phase 2 and 3	
2	ship; D → E	E; phase 2 and 5 phase 5	D; phase 3 phase 3 and 4	
1	water; F → E	F; phase 4 and 5 phase 4	E; - phase 2 and 3	
2	ship; E → F	F; phase 2 and 5 phase 5	E; phase 3 phase 3 and 4	
1	water; Gatun Lake → F	forebay GL; phase a and c phase c	F; - phase 2 and 3	
2	ship; F → Gatun Lake	forebay GL; phase b and c phase b	F; phase 3 phase 3 and 4	

DOWNLOCKAGE ATLANTIC SIDE				
step	water movement or ship movement	measurements in high basin; phase	measurements in low basin; phase	remarks
1	water; D → forebay seaside	D; phase 2 and 3 phase 2	forebay seaside; - phase a	negligible tidal influence
2	ship; D → forebay seaside	D; phase 3 and 4 phase 3	forebay seaside; phase b phase b and c	negligible tidal influence
1	water; E → D	E; phase 2 and 3 phase2	D; - phase 4 and 5	
2	ship; E → D	E; phase 3 and 4 phase 3	D; phase 5 phase 2 and 5	
1	water; F → E	F; phase 2 and 3 phase 2	E; - phase 4 and 5	
2	ship; F → E	F; phase 3 and 4 phase 3	E; phase 5 phase 2 and 5	
1	water; Gatun Lake → F	forebay GL; phase a and c phase c	F; - phase 4 and 5	
2	ship; Gatun Lake → F	forebay GL; phase b and c phase b	F; phase 5 phase 2 and 5	

4 Dry-season measurement programme

Salinity measurements shall be done in lock chambers, forebays, inlets and outlets of the locks, and in selected areas in Miraflores Lake, Gaillard Cut and Gatun Lake. Measurement of vertical profiles of salinity will be done with two, fast response CTD instruments (CTD = conductivity, temperature and depth below water surface). From these measurements both the salinity and the density can be derived as a function of depth below the water surface and as a function of time. These two CTD's may simultaneously be deployed, using two launches, which will be made available by ACP. A third instrument that is connected to a data logger, will be used to measure the salinity at representative, fixed points in forebays at the seaside of locks. These measurements will serve to record salinity levels and salinity variations during a longer period of time.
Positioning in lakes is done with GPS, yielding a horizontal accuracy of typically 5 m. In the locks positioning is done using marks on the lock walls.
Simultaneously with the salinity measurements other relevant data are collected, including date, wheather conditions, water levels, dimensions and type of ships in locks, and lock operation.
The work in the locks and channels will be coordinated by ACP staff.

Starting points for the salinity measurements in locks, forebays and lakes are:

Since East and West lanes are simultaneously used in the same direction, locking processes are similar and there is no need to do salinity measurements in each of the two lanes. The choice in which lane (lock chamber and forebay) measurements will be executed is dependent on traffic and possibilities to fit into the locking scheme.
Prelimenary ship transit schedules are prepared one day in advance by the Marine Traffic Control department (MTC). In consultation with MTC possibilities to execute measurements are discussed and measurements are scheduled in the transit scheme for the next day.
Measurements are planned in the period 8 – 21 April 2002. Balboa will be the home basis for measurements at the Pacific side, Colon the home basis for measurements at the Atlantic side. Transfer from Pacific side to Atlantic side is probably on 15 April, return to Pacific side on 17 April.
Lodging and transport is organized and provided by ACP.

Lock identification:

Miraflores locks:	A = lower lock, B = upper lock
Pedro Miguel lock:	lock C
Gatun locks:	D = lower lock, E = middle lock and F = upper lock

A description of the salinity measurements is presented in the next table: 'Dry-season measurement scheme'.

Dry-season measurement scheme

date	tide	part of day	uplockage downlockage	location of salinity measurements	phase	position of launches	delay expected	remarks
8 April Monday		arrival in evening	lodging in Balboa					
9 April		morning	meeting at ACP office Balboa; preparation of instruments					
		afternoon	launches to Miraflores Landing; preparation of launches; testing of instruments; discussion at MTC (planning measurements in ship transfer schedules)					
10 April	low 08:15 high 14:30	morning	installation of CT logger in forebay seaside Miraflores Locks					
		afternoon	downlockage	forebay ML-south lock B lock B lock A	a, b, c 3, 4, 5 2 2	- astern ahead ahead	12 min. 2 x 12 min. - -	- u/s side of ship - -
11 April	low 09:00 high: 15:15	morning	uplockage low tide	forebay seaside lock A lock A lock B	a, b, c 3, 4, 5 2 2	- astern ahead ahead	12 min. 2 x 12 min. - -	- - u/s side of ship u/s side of ship
		afternoon	-	Miraflores Lake near spillway				
12 April	low 09:45 high 16:00	morning	-	Miraflores Lake in channel				
		afternoon	downlockage high tide	lock B lock A lock A forebay seaside	3 3, 4, 5 2 c, a, b	astern astern ahead -	- 2 x 12 min. - 12 min	u/s side of ship u/s side of ship - -

date	tide	part of day	uplockage downlockage	location of salinity measurements	phase	position of launches	delay expected	remarks
13 April	low 10:30 high 16:45	morning	uplockage	lock A lock B forebay ML-south	3 3, 4, 5 c, a, b	astern astern -	- 2 x 12 min. 12 min.	- - -
		afternoon	-	Miraflores Lake in channel	-	-	-	-
			downlockage	forebay ML-north	a, b, c	-	12 min.	-
14 April		morning	uplockage	forebay ML-north lock C forebay Gaillard Cut	a, b, c 3, 4, 5 c, a, b	- astern -	12 min. 2 x 12 min. 12 min	- - -
			-	Gaillard Cut in channel	-	-	-	-
		afternoon	downlockage	forebay Gaillard Cut lock C	a, b, c 3, 4, 5	- astern	12 min. 2 x 12 min.	- u/s side of ship
			removal of CT logger from forebay seaside Miraflores Locks					
15 April		morning	transfer to Atlantic side; lodging near Gatun Locks					
		afternoon	installation of CT logger in forebay seaside Gatun Locks					
16 April		morning	-	Gatun Lake near spillway, in channel	-	-	-	-
		afternoon	downlockage	forebay GL lock F lock F lock E lock D forebay seaside	a, b, c 3, 4, 5 2 2 2 c, a, b	- astern ahead ahead ahead -	12 min. 2 x 12 min. - - - -	- u/s side of ship - - - -

date	tide	part of day	uplockage downlockage	location of salinity measurements	phase	position of launches	delay expected	remarks
17 April		morning	uplockage	forebay seaside	a, b, c	-	12 min.	-
				lock D	3	astern	-	-
				lock E	3	astern	-	-
				lock F	3, 4, 5	astern	2 x 12 min.	-
				lock F	2	ahead	-	u/s side of ship
				forebay GL	c, a, b	-	12 min.	-
		afternoon	transfer to Pacific side; lodging at Balboa					
18 April	high 08:00 low 14:15	morning	reserve					
		afternoon	downlockage low tide	lock B	3	astern	-	u/s side of ship
				lock A	3, 4, 5	astern	2 x 12 min.	u/s side of ship
				lock A	2	ahead	-	-
				forebay seaside	c, a, b	-	12 min.	-
19 April	high 08:30 low 14:45	morning	uplockage high tide	forebay seaside	a, b, c	-	12 min.	-
				lock A	3, 4, 5	astern	2 x 12 min.	-
				lock A	2	ahead	-	u/s side of ship
				lock B	2	ahead	-	u/s side of ship
		afternoon	removal of CT logger from forebay seaside Gatun Locks					
20 April		morning	concluding meeting at ACP office, Balboa; cleaning of instruments					
		afternoon	preparation of instruments for shipment					
21 April Sunday		departure	from Panama City airport					

Appendix III

Specifications for further studies into salt water intrusion using physical scale models

(Draft Report no 6, dated August 2002)

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Literature

1 Introduction

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 work that is undertaken under the contract is subdivided in eight major work tasks, each work task consisting of a number of clearly defined activities.

In the present interim report, Draft Report no 6, the activities of work task 7 are described. The activities executed under work task 7 include:

7.1 Development of specifications for further studies into the salt water intrusion phenomenon of the Post-Panamax Locks, using physical scale models.
7.2 Draft report no 6, covering the activities of work task 7 (task IVi in ToR).

The following items will be adressed in this report:

- some general considerations with regards to the design of the Post-Panamax Locks
- the phenomena to be studied and simulated in a physical scale model
- scales of the model
- testing facilities
- design and construction of models for Post-Panamax Locks, including filling and emptying system, water-saving basins with conduits and valves
- fresh and salt water reservoirs needed to simulate density currents
- measurement instruments and data acquisition
- operation of the locks, the filling and emptying system and the water-saving basins in the model
- conditions and scenarios for a testing programme
- if relevant, visualisation of density currents
- photographs and video recordings
- analysis and presentation of test results and reporting

A list of general available literature on the subject is presented at the end of this report.

Apart from the study on salt water intrusion phenomena (and measures to prevent salt water intrusion) the physical scale model may also be applied to study other items related to lock design and lock operation. Attention is paid to these items as well in the present interim report.

2 Design of the Post-Panamax Locks: some general considerations

2.1 Introduction

Presently, new Post-Panamax Locks are being designed for a new, third shipping lane of the Panama Canal. The new locks form either a single-lift lock system, a double-lift lock system or a three-lift lock system (the existing locks form a three-lift lock system). Most probably, the new locks will be provided with water saving basins. The overall water-level difference between Gatun Lake and the oceans at both sides of the canal is about 26 m. The nominal dimensions of the new lock chambers are: length 457 m, width 61 m and water depth over the sills 18.3 m. The dimensions of the 'design ship' are: length 386 m, beam 54.9 m and draught 15.2 m.

The filling and emptying time is 8 – 10 minutes for a lock chamber of a three-lift lock system. The water quantity that is required to equalize water levels in adjacent (lock) basins of the three-lift lock system amounts to 26/3 m x 457 m x 61 m = 240,000 m^3; the corresponding average filling discharge is 400 m^3/s (10 minutes filling or emptying time). In next sections we pay some attention to design aspects, also in relation to salt water intrusion.

2.2 Salt water intrusion

When salt-water intrusion to the upstream water basins is to be reduced, design measures can be taken to limit the exchange of salt water and fresh water. Also operational measures are possible to limit this exchange. Another possibility is to flush back the salt water that has passed the lock system. Mixing of salt water and fresh water complicates the effectiveness of measures. Therefore, from theory, strong currents (which cause high turbulence intensities) and a long duration of open locks (enabling full exchange flows) should be prevented. In practice, however, it is generally not possible to choose for a quick lock operation without the generation of turbulence. In view of a limitation of the salt water intrusion it would be advantageous to operate the locks in such a way that the total submerged volume of the ship(s) in the lock chambers is as large as possible. By preference the open times of lock chambers should be kept as short as possible. From the viewpoint of a controled, safe operation a lock chamber provided with a bottom fill / emptying system should be selected for the design.

Considerations with respect to the choice between a three-lift lock system and a single-lift lock system: a three-lift lock system requires more steps in the operation, and the moving ship causes several times disturbance in the water, also because of propellor action, and exchange of water from one lock to another lock; in a single-lift lock system the total volume of water that may be mixed up is larger, and the water use is three times as high. These aspects are treated in the study of the salt-water intrusion for the present situation and the future situation with new locks.

2.3 Lay out of culvert system

Filling and emptying of the lock chambers need to be done with care because the hydraulic forces on the hawser systems may not exceed limit values. The criteria depend on the equipment on board of ships and the hawsers (amount and layout) brought ashore to hold the ship in its position during locking. Maximum allowed forces in hawser systems of VLCC's (very large cargo carrier) are in the order of magnitude of 0.01% of the water displacement of the carriers (criterium valid in Belgium and The Netherlands). Forces due to density differences may already be of that order of magnitude. Consequently, hardly extra forces caused by flow or translatory waves can be absorbed by these hawsers. To prevent the occurrence of strong flows and waves the filling or emptying discharge has to be equally distributed over the length of the lock chamber. For this reason hydraulic losses and inertia effects in culverts need to be about equal for al inflow and outflow locations, which is not an easy design demand and is often not possible. If too strong differences between the inflow / outflow locations arise, one may choose for a design where the cross-sectional areas of culverts are as large as possible. This measure is aimed to limit hydraulic losses in such a way that valve resistances predominantly determine the discharge distributions (even in the case of opened valves). However, two aspects (apart from the construction cost aspect) may be in conflict with this concept:

1 Inertia effects in the culvert system

Inertia effects cause overtravel in the lock chamber. As a result extra time is needed before lock gates can be opened. This overshoot in filling or emptying in case of long culverts is to be assessed with: $\Delta H_{\max} = -\frac{L_c}{\xi}\frac{A}{BL_l}$, with L_c is culvert length, A is culvert cross section, L_l is lock chamber length, B is lock chamber width, ξ is the hydraulic loss coefficient of the culvert system (related to cross-sectional area A). Aggravating factors are a large culvert length and a large culvert cross section; an attenuating factor is a large culvert resistance. By a careful and accurate valve operation overtravel may be limited.

Differences in inertia forces will cause an unequal flow distribution in case that the hydraulic culvert properties are not balanced for all inflow or outflow locations; an unequal flow distribution will result in forces on the ship(s) in the lock chamber. The effects are most remarkable at the end of the filling and emptying process in the case that overtravel is not prevented and circulation of masses of water between the lock chamber and the culvert system occurs (this circulation weakens slowly). This gives an extra reason to limit overtravel.

2. Siltation in the culvert system

Siltation will be promoted when low flow velocities are chosen in the culvert system. Since filling and emptying discharges vary as a function of time, low flow velocities will regularly occur in the culverts. Velocities must raise during certain periods above a minimum level to transport settled silt. If these periods are too short permanent sedimentation will occur. This aspect - on its own - may lead to a choice for small culvert cross sections.

However, if marine growth is expected the hydraulic resistance of culverts with small cross sections may increase considerably. In that case large culvert cross sections may be the better choice; this allows some marine growth to occur and does not immediately lead to

unacceptable effects. Appropriate maintenance possibilities of the culvert system should be considered during design anyhow.

2.4 Other aspects

Air entrainment

The general design of the culvert system should be such that entrainment of large volumes of air is prevented. Air bubbles in the filling discharge popping up in the lock chamber cause hindrance for small ships (pleasure craft), adversely influence discharge distributions during filling or emptying and may cause impact forces on culvert valves in case that air volumes suddenly disappear through gate shafts.

Entrainment of air may appear at the entrances of the culvert system (for instance by vortex flow) or at the downstream side of gates or valves when culvert ceilings are not deep enough designed. This depends also on details of the design of valves or gates and recesses. Air should not remain trapped in the culvert system.

Operation of culvert valves or gates

Culvert valves or gates should such be operated that forces on ships are within preset limitations. Whether this can be achieved is depending on the hydraulic characteristics of the filling and emptying system. When overtravel phenomena occur at the end of filling or emptying of the lock chamber, valves or gates should be closed to dampen the oscillations. A correct timing of this closure procedure is extremely important.

Opening of lock gates

At the end of filling or emptying of the lock chamber a water level difference across the lock gates will exist (density differences cause unequal forces on the lock gates; they balance when a small water level difference is maintained). The stability of the lock gates during opening should be guaranteed and opening of the gates carefully done because of possible wave and current forces on ships.

Approach harbours

During emptying or filling, flow effects and translatory waves are also generated in the approach harbours. Waiting ships may experience forces and a check on possible effects is advisable.

Maintenance and repair

Maintenance and repair of shipping lock components is one of the aspects that should be taken into account during design. Gates and valves should be replaceable by spares, culverts should be maintainable (in view of siltation, marine growth).

3 Phenomena to be studied and simulated in a physical scale model

3.1 General

The question that has to be answered before guidelines can be given about scale model studies into the salinity intrusion process of the new Post-Panamax Locks (or other aspects) is what purpose has to be served with the scale model. A scale model cannot be considered as a complete replica of an in-situ situation, but is always built to investigate predetermined aspects. The model is constructed on a scale and with certain model operation possibilities aimed at these aspects. Therefore, first the main ideas about the designs and operations of the new locks should be made clear, the main hydraulic characteristics be assessed and the critical points be agreed upon. The investigation approach should be directed to these critical points.

The salt water intrusion to the upstream basins may form the principle subject of the investigations. As hydraulic scale model tests are always directed to obtain answers on some key problems, a series of tests under well defined schematized conditions will fulfil. Salt water intrusion is the result of hydraulic proceses which are governed by many factors; parts of the process can be computed and parts need to be verified with tests in a scale model or, later on, in-situ. A mixture of computations and tests should be chosen to make an as correct as possible prediction of the salt intrusion phenomenon.
For the set up of the scale model it is important to know on what aspects the tests should be focused on. Apart from focusing on the salt intrusion process, other aspects such as the safe operation of the locks (in view of hydraulic forces on ships) and the filling and emptying system design may also be the subject of the scale model study.
Focusing on various aspects does not necessarily mean that a complete lock system has to be modeled. For instance, in the case of the three-lift lock system only one lock chamber is necessary. And in the case of the single-lift lock system the most important phase of the locking process can fully be simulated, while for other phases a more schematic simulation may be sufficient.

3.2 Necessary data

For the purpose of setting up the study approach and designing the scale model and the test program, knowledge of the following is necessary:

- general conditions (head, density differences across the locks, tide, wind, silt content of water)
- the design of the new Post-Panamax Locks and water saving basins (dimensions, type and lay out of filling and emptying systems, measures to limit salt intrusion, if any)
- the foreseeable operation of the locks (filling and emptying times, open time of lock chambers, occupation of lock chambers)
- the traffic that will pass the locks (types of ships, ship dimensions, transit frequencies, ship manoeuvres)

- the hydraulic phenomena that are relevant for salt intrusion (turbulent mixing, entrainment, exchange flows).

3.3 Items that can be studied in the scale model(s)

A correct simulation of the locking process is necessary to allow a reasonable assessment of the salt intrusion. But a lot of aspects are entwined and influence each other. As stated above, not all effects can be investigated in a hydraulic scale model and calculation methods should be applied also to cover the other aspects and to couple (various sources of) information such that an overall estimate of effects can be made.
Although the advise is to be directed on salt intrusion effects, the investigation methods to be applied make it convenient to combine the study with other relevant aspects, such as the hydraulic functioning of the leveling system (leveling times, overtravel aspects, pressures in culverts, (prevention of) air entrainment), forces on ships, forces on lock gates, etc.
For instance:

- The new locks may be equipped with other gates than used in the existing Panamax Locks (which are provided with miter gates); both the different type and size of the new gates cause a greater vulnerability to density differences.
- During operation density differences may cause forces on ships in the lock chamber, like in the existing situation, but with bigger ships these forces may become higher (it depends also on the designs of the new filling and emptying systems).

Hydraulic scale model investigation of Post-Panamax Locks may probably be directed on:

- the filling and emptying times,
- the forces on ships during sailing in and out of the lock chamber,
- the forces on ships during leveling,
- the intrusion of salt water in upstream basins,
- the proper functioning of lock gates, and valves.

3.4 Pros and cons of scale model investigations

Scale model investigations are helpful tools to demonstrate relevant hydraulic effects if

- the model area is sufficiently large
- model scales are properly chosen,
- model boundary conditions are properly simulated and
- correct measuring techniques are applied.

However, schematized conditions always exist in scale models:

- the human factor (e.g. in lock operation) is reduced,
- a model test simulates a schematized in-situ situation (all kind of real, time dependent in-situ processes are difficult to simulate in the model, like tidal movements, salt concentration variations, ship traffic, wind effects etc.)
- not all phenomena can be simulated in model (for instance silting up will not be on scale)
- scale effects and model effects are present.

Nevertheless these cons, scale model investigation is regarded as an indispensable method to investigate possible future effects related to the Post-Panamax Locks. Next important conditions have to be fulfilled:

- ample experience with the type of phenomena to be studied,
- design of the models and testing programs is primarily directed to the relevant phenomena
- scale and model effects should be kept sufficiently small.

3.5 Study approach

In the case of the Post-Panamax Locks an important issue is the salt water intrusion to the upstream basins. The salt intrusion depends on the layout of the locks (e.g. steps in floor), local entrainment phenomena, diffusion and mixing effects over longer distances, the ship traffic characteristics and the operational management of the locks. A simulation of various scenario's will be needed to reach a reliable prediction.
Scale modeling is advised in combination with mathematical modeling or calculation methods to take advantage of the strength of both modeling techniques. Generally, such a coherent approach is always chosen when overall effects are studied; the strength of physical scale modeling lies more in the detailing. From an analysis of factors which influence the salt intrusion process (the analysis should include seasonal effects, wet and dry periods, tidal effects, influences from traffic etc.), an over view of the most important aspects of the salt water intrusion process can be derived which need further investigation. The tests in hydraulic models are to be focused on those components, which are related with the design and operation of the locks. Eventually the total salt water intrusion effect is to be studied with mathematical modeling or calculation methods, fed by the results of the scale model investigation.

3.5.1 Dimensions of approach harbours in scale model

Special attention is needed for the simulation of phenomena related to density differences. Related aspects are: slow variation of internal (density) waves, mixing due to propeller action, water level differences across lock gates while culvert flow is at rest, large forces on the ships due to density differences in front harbours, during sailing in and sailing out of the shipping lock and during the leveling process. Density differences cause forces which may act both in longitudinal and transverse directions on the ships.
A question to be answered before deciding on the size of the model is whether sailing of ships in and out of the lock chamber

- influence the density in culverts which are open to the lock chamber (this may result in important differences between the model and the real situation),
- result in strong inertia effects of internal waves (this may influence the forces which act on the ship and may complicate control over the ship).

When ship manoeuvres in approach harbours need to be simulated, the model has to be provided with approach harbours of sufficient length to allow - at least partly - starting and stopping manoeuvres of ships without affecting too much the internal flow phenomena in the approach harbour. (Moreover, scale effects occur when ship propeller action is simulated in scale models. A combination of an external force applied on the ship and propeller action is often necessary.)

At least short parts of the approach harbours are necessary in the scale model to (simply) handle ships, to sail with propelled ships into and out of a lock chamber, to be able to simulate near field flow patterns and to allow a correct propagation of translatory waves which are produced by the leveling processes.
A minimum length of approach harbours of three times the ship length should suffice for that.

3.5.2 Modeling of the shipping lock system

Several types of lock systems are still possible: single-lift, two-lift and three-lift systems in a single lane, with or without water saving basins. Probably the same lock type will be chosen at both sides of the canal.
In the model set up a balance should be found between an adequate reproduction of the lock systems such that the phenomena of interest can reliably be studied, and the complexity of the model in view of operation. Moreover, if as a result of the investigation changes in model are necessary a limited model set up will show to be advantageous. When for the purpose of the investigation only one lock chamber out of three is sufficient, it is advised to reproduce only one lock chamber.

4 Modeling aspects and scales of the models

4.1 General

In general scale effects will exist. Question is how to choose scales such that reliable results are achieved and a manageable model is used. Manageability is also very much dependent on the approach during the design with items as computerization of (a part of) the model operation, available space for the model, equipment, experience of personnel. 'Manageability' depends therefore also on the skills of the laboratory that is selected for execution of the studies.

Scale effects are due to friction of water flowing along surfaces, internal friction at the transition of fresh water flow to salt water flow, mixing of salt water and fresh water and surface tension effects. Other scale effects are less relevant in this case. Important aspects must be modeled as correct as possible; less important aspects may suffer from some scale effects but can possibly corrected. It may be necessary to compromise on this and to make detail models for local phenomena that cannot be simulated on a scale that is acceptable for an overall model.

In general one set of scales is chosen for a hydraulic scale model. In this case this is imperative.
As local flow patterns are important, horizontal and vertical scales are to be chosen equal in order to allow the same ratio of vertical en horizontal acceleration in model and in-situ (non-distorted model).

4.2 Modeling of gravity driven flow

Filling and emptying flows are governed by gravity and for a correct simulation of flow phenomena the same ratio of horizontal and vertical forces in model and in-situ is needed. This is achieved by Froude scaling, which means that the Froude numbers in model and in-situ are the same at all locations and at all times. The Froude number is defined as $F = \frac{U^2}{gH}$, with U = velocity (m/s), g = gravity (m/s^2), H = depth (m). As both gravitation and the mass of water are the same in model and in-situ, the velocity scale is equal to the root of the length scale and all other scale rules can be derived from this : $n_U = \sqrt{n_l}$. Also density-difference driven flow will be on the same scale when the same density differences are applied in model and in-situ. For this the 'densimetric Froude number' is defined: $F_i = \frac{U^2}{\frac{\Delta\rho}{\rho} gH}$, with $\Delta\rho$ = density difference (kg/m^3) and ρ = density of water.

4.3 Viscous effects

Scale effects may occur in the model. Most important are the viscosity effects, also called Reynolds effects, which occur because the viscosity of the water in the model is not scaled. These effects are most apparent at boundaries and in the detachment of flows from surfaces. Also turbulence levels in the fluid may be influenced. The Reynolds number, representing the ratio of inertia and viscous forces: $\mathrm{Re} = \frac{UD}{\nu}$, with U = velocity (m/s), D = typical dimension and ν = kinematic viscosity (m^2/s), is not reproduced when the viscosity is the same in the model and in-situ. Viscosity effects in model are always more important than in-situ, but these effects should not prevail in such a way that model results cannot be compensated for that. In the in-situ situation often rather smooth walls with a turbulent boundary layer exist, while in model these walls are smooth but with a laminar boundary layer; this leads to a lower (but too high) limit for wall friction.
In a lock model especially culvert flow will be influenced by friction. The energy loss due to friction may be assessed with $\Delta H = \xi \frac{U^2}{2g}$, with $\xi = \lambda \frac{L}{4R}$. L = length of culvert, R = hydraulic radius of culvert section. The coefficient λ can be read from presentations of Nikuradse data and is a function of Reynolds number and the hydraulic roughness of the culvert lining. One should verify the in-situ roughness of the existing locks to learn about the roughness to be taken into account for the design of new locks. Marine growth can have a significant influence on the roughness of the culverts and even cross sections may be narrowed.
If marine growth occurs, maintenance may be necessary by cleaning the culverts from time to time. In the scale model study on salt water intrusion one may opt for mean circumstances. Marine growth has effects on the filling and emptying characteristics, and thus on forces acting on ships.

In case that marine growth does not occur and a reasonable smooth lining exists in the in-situ situation, due to viscosity effects the filling and emptying discharges in the scale model will be somewhat smaller and the filling and emptying times larger than in an ideal model. Subsequently, other phenomena as pressures at culvert ceilings downstream of valves and vortices at entrances are influenced. The Reynolds effect on the discharges and filling and emptying times should be small enough to avoid that the model is not a close representation of phenomena in-situ. If culvert cross sections are modest, the Reynolds effects in model will be stronger. Counter acting measures are to design larger cross sections and/or shorter culvert lengths in the model, but these measures are less suitable in a lock model with simulation of filling and emptying flows, as inertia phenomena will adversely be effected.
When marine growth is expected, a full assessment of it's effect should be made. The model roughness may be about correct or - in case of strong marine growth - even too little, when standard plate material is used for construction of culverts. In the latter case the plate material needs to be lined with a roughening material.

4.4 Mixing processes

With respect to density flows some extra demands are to be considered. Additional to wall friction effects (see above), also the internal shear layer between fresh and salt water flow

may be influenced by the viscosity effects. This may be relevant if density flow over long distances needs to be simulated.

The generation of turbulence will be influenced by viscosity effects and it is relevant that both in the scale model and in the in-situ situation these influences are about the same. A characteristic quantity to assess this aspect is the Richardson number, which shows the ratio between the buoyancy to inertia force gradients and is a direct measure for the stability of a density stratified flow. The Richardson number is defined as: $R_i = \frac{-\frac{g}{\rho}\frac{d\rho}{dz}}{\left(\frac{du}{dz}\right)^2}$. It can be shown that if the densimetric Froude number is preserved, also the Richardson number will be preserved.

4.5 Modeling of density flows

In general local density flow phenomena cannot be investigated in a model with distorted scales, while far field phenomena can be investigated in a model with distorted scales. Next table shows some examples.

phenomenon		remarks	maximum (vertical) scale
Internal density flow in the lock chamber of a shipping lock		Scale distortion allowed little influence of viscosity	80
Salt water flow from the lock onto a deep salt water pit in the front harbour, including mixing	Local phenomenon	No scale distortion allowed; little influence of viscosity; air curtain reproduction is a problem	
Internal translatory wave, including damping in salt water pit	Far field phenomenon	Influence of viscosity due to long distances; scale distortion advised	20
Reflection of internal translatory wave on slopes of the salt water pit		Distortion of scales is allowed	
Flow onto a deep laying slot for selective withdrawal	Far field phenomenon	Influence of viscosity due to long distances; scale distortion advised	20
Selective withdrawal at a deep laying slot	Local phenomenon	Reproduction of salt concentration important; distortion of scales is sometimes allowed, depending on the lay out of slot	80
Entrainment of salt water by flushing in canal	Far field phenomenon	Only qualitative reproduction due to lack of traffic effects, lack of wind effects and scale effects in diffusion	

4.6 Ship movements in model

When self-propelled ships are applied in the scale model study one should take into account scale effects due to viscosity differences between model and in-situ: skin friction leads to larger forces in the model to keep the ship at a correct speed and the propeller is less

effective in the model. The effect of skin friction is the most important of the two. It implies that extra propeller speed is required, which leads to more turbulence and mixing in model. For that reason model ships are sometimes trailed by cable in combination with propeller action. In the present case ships will have a low speed and propeller action is used to accelerate or decelerate the ships, which sail in narrow areas (lock chambers and forebays / tailbays). The effects of added water mass and drag resistance are more important in restricted water than in wide water. Added water mass effects are less sensitive for scale effects, but drag resistance may deviate in the model. For that reason it is advised to carefully consider the possibility of self-propelled ships in the scale model with extra cable trailing.

4.7 Air entrainment

Air entrainment by flowing water cannot easily be simulated in the scale model as the surface tension is a property of the fluid. The Weber number, representing a measure for the surface tension, should be reproduced, but this demands a large model. The surface tension may be influenced to some extent by application of detergents. A threshold value of the water velocity of about 1 m/s exists before air is entrained. When air entrainment is to be checked in the scale model, this is done by studying the flow patterns, check of strong vortex formation, analysis of overpressures in culverts and by consulting experience. The distribution of entrained air in a small model will not be the same as in the in-situ situation. Air entrainment by low pressure zones downstream of valves or gates can be investigated in a hydraulic model, assuming that details of the structure (gate recess, gate upper lips, etc.) are accurately reproduced. Detail models may be necessary when this aspect is critical.

4.8 Cavitation

Cavitation cannot be simulated on scale in normal free surface scale models. The Thoma number can not be reproduced as the atmospheric pressure is the same in the model and in the in-situ situation. When cavitation is feared one should analyse the cavitation conditions, like flow velocities and pressures, in the scale model or by computation. The leveling process should be controled in such a way that cavitation is limited. In free surface flows (for instance in spillways) often aeration is applied to minimize cavitation induced erosion. In general, strong aeration is not a measure applied in shipping locks to dampen the effects of cavitation, because aeration will result in other, adverse effects. Air pockets in culverts may influence pressures in culverts, affecting discharge distributions in a rather unpredictable and erratic way. Large air pockets may suddenly disappear from culverts through gate shafts resulting in shocks on culvert ceilings and gates. However, cavitation is a dangerous phenomenon for the structures and shipping lock equipment. Because of the short duration of cavitation in culverts of shipping locks (compared to other hydraulic structures where a more permanent or long lasting flow may appear), a modest level of cavitation is often allowed. In the case that water level differences are less than about 12 or 13 m (like in the Netherlands), cavitation should not be a problem. At higher heads (like Panama Canal Locks) design should take into account the possible effects of cavitation by, for instance, choosing sufficient gate depths, application of special gates, lining of culvert sections, adapted gate operation, limited aeration. No specific literature about measures to reduce cavitation effects in shipping locks is available. A few design offices and institutes are

experienced in this field. It is advised to investigate the descriptions of high head shipping locks in the proceedings of PIANC.

4.9 Siltation

Siltation will not be on scale in the model. Siltation is a time dependent process; because in a scale model the sequence of conditions is not the same as in-situ, quantitative results are not correct. Moreover, siltation is a complex process wherein flocculation governs the effects in salt water fresh water regions. Also, the presence of silt would complicate the investigation; it is advised not to apply silt in the scale model. An impression of locations where siltation may occur can be obtained from the model by checking the existance of stagnation zones. Also a mathematical approach is possible.
It is important to assess the possibility of siltation in view of the design of culvert cross sections and in view of maintenance.

4.10 Accuracy of modeling

To a certain extent a scale model of a structure is a schematized reproduction of the real structure. The exactness of the realised model is depending on the accuracy of the workshop and the materials that are applied (effecting shape, wall roughness, rigidity etc.). Culvert cross sections may differ easily a few % in size, incorrect shaping of valves may easily result in other stage discharge relationships. It is advised to jointly limit scale and model effects in discharges within 5% to 10% of the real values. Also when the total effect is known, relevant model results should be checked. The influence of scale (and model) effects on all sorts of measurement results (discharges and flow velocities, filling and emptying times, pressures in culverts, forces on ships, etc.) should be assessed beforehand.
It may be necessary to check the effect of schematizing important model details (for instance model valves) beforehand in separate tests, and decide then how to simplify these details.
The investigation program should start with acceptance tests to demonstrate the differences, if any, between the scale model and the in-situ situation (the latter analysed through analytical or numerical computations).

4.11 Conclusions

From the previous sections one may conclude as follows:

- A non distorted model of a lock system should be constructed on a length scale that is convenient with respect to general scale effects (not taking into account density flow effects). The choice of the length scale is also dependent on the possibilities of the workshops. A length scale of 40 to 60 may fulfil in case that in-situ culverts are smooth.
- A larger model has to be constructed when culvert cross sections are relatively small. In this model no exchange flow over long distances can be investigated.
- In case of marine growth in the in-situ situation (causing rough walls) length scales up to 80 may be possible, but the situation before marine growth has developed can not be checked accurately enough in this model.

- When filling and emptying of the locks is not investigated in the scale model, and tests are only focused on the flow in the approach harbours and lock chambers, length scales up to 80 can be chosen.

5 Testing facilities

The required testing facility is rather simple because the model of the locks, including all basins, has fully to be constructed. When the research station is equipped with a salt water installation, this is advantageous. Experience with the simulation of density flows may a priori prevent a certain category of mistakes. It means also that measuring equipment is available. Application of salt water in scale models implies that corrosion of vulnerable model parts may occur. Application of stainless steel and synthetic material are preferred, at the disadvantage of higher model construction cost. Conduits, pumps, frames, instruments may be written off after the investigation or be replaced one or more times, depending on the duration of the investigation.
Salt water is finally sluiced to a sewer system and this should be allowed (municipality regulations may be rather strict). One should, by preference, prevent large temperature differences between model water and storage water as this will influence the density.

It is important that the foundation of the model is firm, that means a concrete floor is preferred. Simulation of water level differences across the model is important; without firm foundation the subsoil of the low-level model part may be weakened, which may destroy the model or bring the model in disorder.

A sheltered or indoor model place is preferred because of the better possibilities to take photographs of flow patterns and water-temperature control. However this is also dependent on techniques that are applied. Tests during night time are also possible, if necessary.

6 Scale model design

6.1 General

Before 'testing facilities and model design' can be discussed, first the list of 'unknowns' should be agreed on; than the investigation approach based on that list can be chosen. In this section rough ideas for scale model investigations are given; the research station shall make a more attuned study proposal after lock designs are known and study items are explored and agreed.
It is most likely that the study will comprise of a mix of questions related to salt water intrusion (and measures to reduce salt water intrusion) and questions related to design and operation of the locks. The culverts of the filling and emptying system are an example of the latter.

In a scale model investigation one should choose for well defined test conditions, which can be repreduced at wish in order to be able to draw conclusions on the basis of series of tests. Test series should therefore carefully be designed and strict regulations with model test preparation should be applied.

This holds in particular for the present case where density flow effects form part of the subjects to be investigated. The reason is that all hydraulic changes in the model (which are also easily exaggerated in the model) will generate internal, density-driven waves and turbulence. Internal waves have a low propagation speed and damp out slowly, while turbulence causes mixing. It takes time before a model is at rest and ready for the start of a test. Carefully planned and with patience executed tests will yield much better results than a large amount of hastily executed tests. This demand is to be granted especially if stratification has to be simulated in the model.

During the design of the model it is strongly advised to take care of this aspect and to invest in measures to facilitate quick but quiet operation of the model. Special reservoirs are needed for fresh and salt water, which are kept at the correct density and at the same temperature as in the test hall. One should reckon with regular spillage of brackish water to a sewer system.

6.2 Model boundaries

Common with scale model investigations of shipping lock systems is the separate regulation of water levels at both sides of the shipping lock system. These levels will be kept at a certain elevation during a test, but need to be regulated to simulate other water levels at sea, lake or canal sides. Model boundary structures should be designed in such a way that no or only minor reflection of translation waves occurs from these boundaries during filling or emptying. Good experience exists with movable long overflow weirs sustained by some water circulation at the model boundaries.

Circulation discharges at the model boundaries should not be underestimated. To make reflection free boundaries next equation may be applied: $Ql^2 = 0.07B^3c^3$, in which Q = circulation discharge at the model boundary, l = length of adjustable (zigzag) weir at the model boundary, B = width of approach harbor, c = celerity in approach harbour. The circulating discharge may also be functional in mixing the water of the approach harbour so as to maintain a constant density.

6.3 Operational aspects of the model

Other important aspects of for the design shipping lock models are:

- leakage at gates and valves,
- exact control (and repeatability) of the operation of gates and valves,
- position and occupation of ships in the lock chamber
- measurement of forces
- measurement of salt water: position of mixing layers and velocities
- measuring of water levels

Leakage in scale models with density differences should be prevented as much as possible. Probably inflatable seals are necessary which should be carefully manufactured. Modeling details of structures is important and good workshops are essential.

Control of the operation of gates can be chosen in different ways, depending on the experience of the research institute. Computer steered valves may be an expensive choice but are very useful, in particular when combined with data acquisition. This approach is strongly advised.

Depending on the type of filling and emptying, often investigations are made with a single, major ship and a number of smaller ships in the lock chamber. If the situation is acceptable for the biggest ship, it is not always true that this holds for smaller ships as well.
Forces on ships should be measured during leveling and without influencing the free movement of the ship, except in horizontal direction where one can decide for simulation of a certain spring stiffness.
Large ocean going vessels are equipped with tension winches and during the locking process one preferably uses these winches to control the ship. In thes case of the Post-Panamax Locks most probably engines ashore will handle the ships and hawsers on board are put on bollards.
The investigation should reckon with maximum allowable forces which depend on the equipment ashore including the set of hawsers brought ashore (and the angle of these to the ships' axis) and the operation of hawsers ashore. The larger the ship the lesser the allowed hawser forces will be. A separate study is necessary to conclude on allowable forces depending on the ships weight.
In case of very small ships (pleasure craft for instance) also other criteria are relevant, such as local cross currents (due to filling or emptying, but also due to propeller action from bigger ships that are handled simultaneously), wave heights, etc.
Handling of ships in the shipping lock may be eased by application of a stiff measuring bridge. Force measuring at the ships is often done without influencing the free rotation possibilities a ship has, except for sway. The longitudinal force is measured at a single point in the rotation axis of the ship. If some longitudinal displacement of the ship is of interest,

one may consider a certain spring stiffness in the force measuring system. General knowledge about force measuring systems is indispensably. Ballast weights in the model ship should properly be placed.

Special laboratory measuring equipment exists for measuring the density of water and the flow velocities and flow directions. Before the test starts measurements shall be made of the density at reference locations. During the test it will be necessary to measure the density flows (continuous measurement of the position of the interface between fresh and salt water and the velocities and directions of salt water flow).

Water level measurements before and during the test will be necessary to control the water levels in approach harbours and lock chamber. This can be done with water level followers or accurate pressure cells. The advantage of a water follower instrument is the independency of water density.

Data acquisition is preferably combined with control of the model. Each institute will have its solutions for that. The advantage of such a combination is that the manageability of the investigation is favoured and the analysis of test results is quicker done.

6.4 Conditions and scenarios for a testing programme

The testing programme is to be decided after details are known of the new locks and the ideas about how to operate. First a theoretical analysis of the filling and emptying process is necessary to analyse the critical parts, and then a decision has to be taken what study approach is necessary.
It is advised to do tests both for the biggest ships that can pass the locks, for frequently passing ships, and for small ships. It is also advised to investigate extraordinary filling and emptying procedures because of the possible events of malfunctioning of culvert valves or gates.
It is advised to set up a systematic test program, changing one item at a time, and to conclude with tests wherein several items are changed to check for independency of test results.

6.5 Visualization of density currents

Visualization of density currents is possible by color dye injection. It is advised to chose a permanent blue, non toxic type and to apply small amounts of another colour to study local phenomena.
Flow patterns are influenced by density currents: surface and bottom flows have a more spreading character than homogeneous flows. At the water surface floaters may be used to visualize this effect. Special floaters may be used to indicate the bottom flow pattern in some way.

6.6 Photographs and video recordings

Photographical techniques and video recording techniques may be applied in combination with tracers or floaters to demonstrate, visualize and record density flow phenomena and to compare with mathematical model results, if any. New developments are available in digital

video recording in combination with software for visualization of flows. As the purpose of the scale model studies differs from developing analysis techniques, it is advised to apply standard available equipment and methods.
For flow pattern photography a model hall without direct daylight influence is advised.

7 Analysis and presentation of test results and reporting

The report of the model investigation should at least contain:

- duties of the hydraulic institute with respect to the project
- general description of the locks, approach harbours and traffic
- description of hydraulic circumstances and conditions
- data on ships and allowable forces
- description of the lock systems and subjects to be investigated
- hydraulic analysis of the filling and emptying systems
- if mathematical modeling is adequate, the relation with the physical model study
- description of test programs
- description of models and model operation systems
- description of data acquisition and analysis system
- plane results of the tests
- description of phenomena learned in the models
- proposals for alterations and conclusions from discussions with Client
- test programs to check the effects of the alterations
- conclusions

The report should contain enough tables, figures and photographs to enlighten the results and conclusions. A general video movie of interesting tests should be composed.

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