Review of Saltwater Intrusion and Mitigation Studies and Models for Proposed Post-Panamax Locks

Final Report

November 2005

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1 EXECUTIVE SUMMARY AND CONCLUSIONS

In accordance with Work Order No. 18, Contract No. SAA – 151798, dated 13 April 2005 'Review of Possible Salt Water Intrusion and Mitigation Studies and Model for Proposed Post–Panamax Locks at the Pacific and Atlantic Sides of the Panama Canal' DHI Water & Environment has been commissioned by Autoridad del Canal de Panamá (ACP) to prepare a review of the studies undertaken to investigate salt intrusion.

The salt water intrusion studies are awarded to WL Delft Hydraulics and presented in Reports A, B, C, D and F, see the table below. This report describes the results of the review of these studies.

Study SAA-74337	
Report A	*Salt Water Intrusion Analysis Panama Canal Locks, Existing Situation, Report A June 2003, Delft Hydraulics*
Report B	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Single Lift Locks, Report B September 2003, Delft Hydraulics*
Report C	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Three Lift Locks, Report C September 2003, Delft Hydraulics*
Report D	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Two Lift Locks, Report D September 2003, Delft Hydraulics*
Study SAA-135358	
Report F	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Study, Modelling and Analysis of Salt water Intrusion Mitigation Systems for Revised 3-lift Lock Configurations, Report F April 2005, Delft Hydraulics*

The following observations have been made:

SWINLOCKS

The salt water intrusion into the Gatun and Miraflores lakes is simulated by the Salt Water Intrusion in Locks (SWINLOCKS) model. SWINLOCKS is a box model based on conservation of volume of water and salt. Measurements, theoretical analysis and numerical hydrodynamic (Delft3D) simulations empirically determine salt exchange coefficients. It integrates the different time scales into single events: equalising, density flows and ship movement. The model is used both for simulation of the salt exchange between locks as well for simulation of the salt exchange between the locks and sea and between the locks and the lakes. The model is designed for calculation of the salt water load on Miraflores and Gatun Lake.

Salt Exchange between locks

Based on independent salt intrusion computations it is confirmed that SWINLOCKS calculates correctly the salt exchange between the locks. The critical factor in SWINLOCKS is the exchange coefficients. Although the determination of the coefficients is associated with a large scatter it seems that the coefficients applied between the locks are sound and robust. Field measurements and data collection within locks are

adequate for the purpose although a large scatter was found. Only minor inconsistencies have been identified. It is concluded that the SWINLOCKS model describes the salt transport from lock to lock with sufficient accuracy.

Salt Exchange in Gaillard Cut
Very low salinity is observed near Pedro Miquel forebay (order of 0.1ppt). It is known that about 1% of the mechanical energy for ship movement is available for water column mixing. As the density difference (equivalent to 0.1ppt) is very low, an order of magnitude calculation gives that ship propulsion will mix the water column in Gaillard Cut over the vertical. As a result it must be expected that salinity will be transported back through Pedro Miquel Locks with the spillage water. Consequently, DHI expects that almost no salt will be transported from the Pedro Miquel Locks through the Gaillard Cut into the Gatun Lake. Whether this also can be expected to be the case for the new locks needs to be supported by numerical simulations.

Salt Exchange between Lock - Lakes
Salt intrusion into the lakes depends on the size of the ships, number of ship passages, lock operations, turn arounds and is a balance between salt inflow from the upper lock, salt density driven flow away from the lock and the salt outflow due to spillage. Salt concentrations decrease gradually away from the locks. It is the opinion of DHI that the variation in space and time of salt close to the lock is decisive for correct determinations of the salt outflow during spillage and thereby the net salt import/export.

A box model of the lakes with three compartments only can not describe the salt gradients near the locks. The SWINLOCKS model describes the salt exchange between locks and lake taking all the processes into account empirically. A box model approach alone to describe the salinity conditions in the lakes cannot be used to predict the present situation and the full consequences of the Post-Panamax locks. This has been demonstrated by a series of 3D hydrodynamic simulations of salt water intrusion.

Field Measurements in Lakes
Salinity levels in Gatun Lake and Gaillard are very low, less than 0.1ppt. The applied CTD instruments could not detect salinity below that level. The only conclusion drawn in Report A from the measurements was that salinity is less than 0.1ppt in Gatun Lake and Gaillard Cut. However, though salinity values are low, DHI expects the variation (ratio between salinity at forebay and central Gatun Lake) to be high. It is recommended that new measurements must be made in the vicinity of Gatun and Pedro Miquel Locks. In freshwater, ion concentration may equally consist of a number of salts other than Natrium Chloride. Conductivity is thus not equivalent to NaCl. It is recommended that the different salts that are present in the Lake water are measured in order to determine the origin of water. Conductivity must be measured with a high precision instrument designed for freshwater applications.

Water Saving Basins
In Report F Delft Hydraulics has calculated the effect of introducing water saving basins for the Post-Panamax Locks. In the SWINLOCKS model the water saving basins (WSB) are lumped together, described by the water volume and the average salt concentration in the basins. This approach can be confirmed by DHI.

Analysis of Mitigation Studies
A total of 10 mitigation schemes have been identified by Delft Hydraulics, Report F. This identification is considered complete. Concerning the determination of exchange coefficients for the salt pit mitigation scheme it is noted that it is based on 2DV Computational Fluid Dynamics simulations. However, the flow around the pit must be expected to be strongly 3-dimensional. The analysis must be complemented with 3D flow simulations.

Further Investigations
Based on the review summarised above, the following further investigations are proposed in order to complete the understanding of the salt water intrusion both in the present situation and after construction of the Post-Panamax Locks.

Improve the knowledge of the flow and salinity gradients in the lakes in the vicinity of the existing locks by a combination of measurements and 3D model simulations. Salinity measurements must be prepared for very low salinity values and supplemented with water sample analysis to define the chemical composition of the lake water as well as in the tributaries to establish the proper background salinity. Salinity measurements could be supplemented with tracer studies to provide an independent measure of the intrusion of seawater into Gatun Lake.

Determine by 3D modelling the flow and salinity gradients in the lakes in the vicinity of the Post-Panamax locks. Identify the salt exchange and possibilities for enhancement of mitigation schemes related to maximise return flow of salt water with spillage.

Determine the long-term salt concentration in the lakes (time scale years) after construction of Post-Panamax locks by a combination of 3D simulations and a lock model. A procedure for such a combination is not simple to establish, as the salinity close to the locks varies with each up- and downlocking, whereas far from the locks the variation is much slower with a time scale of month to years. To determine the long-term salt concentration it requires that both time scales are resolved in the model. An approach for simulating both time scales is described as part of the review.

Establish a long term monitoring programme of salinity and biology. This programme should be supported by a water quality (salinity model) of the canal system and an analysis of the biological sensitivity of the system with respect to salinity changes.

2 BACKGROUND

The Panama Canal is an 80 km long, three-step lock waterway connecting the Atlantic and Pacific Oceans across the Isthmus of Panama. The Autoridad del Canal de Panamá (ACP) is the autonomous entity of the Government of Panama tasked with the administration and operation of the Canal since 1 January 2000, following the transfer from the United States of America's stewardship by virtue of the Panama Canal Treaty of 1977. The object of the studies undertaken by ACP is to study the possibility of further expanding the waterway's capacity in the near future to allow the transit of larger Post-Panamax vessels. To ascertain the envisioned traffic demand and to formulate the expansion options, the ACP is developing a programme of studies integrated into what has been denominated the Panama Canal Master Plan, currently in its draft phase.

The existing Panamax canal system, consisting of sets of locks and dams at the Pacific and Atlantic ends and fresh water sources from rivers and watershed, has preserved the Gatun Lake mainly as a fresh water body.

Early studies indicate that a new set of Post-Panamax locks depending on operation and ship mixes may increase salt water intrusion into the Gatun Lake. For this reason, the ACP has awarded three salt water intrusion studies to WL Delft Hydraulics:

1. SAA-74337 Salt water intrusion studies in new Post-Panamax locks of the Panama Canal: salinity measurements were conducted in the existing locks and lake system to prepare and calibrate a numerical model for the actual conditions. The model was later modified to include new Post-Panamax locks and simulation runs made to predict expected salt water intrusion due to the operation of new locks for different configurations of 1, 2 and 3 lift locks; combinations of none, two, three and six water saving basins; different traffic intensity of 5, 10 and 15 lockages per day in the new locks; varying the Gatun Lake levels and water management alternatives.

2. SAA-110830 Salt water intrusion study due to water recycling system in the Pacific Post-Panamax locks: the numerical model was modified to predict salt water intrusion for different configurations of a water recycling system in the new locks at the Pacific side. Due to the high salinity results, the pumped water recycling alternative is considered disadvantageous and will not be reviewed under this contract.

3. SAA-135358 Mitigation systems for salt water intrusion for new Post-Panamax locks: different mitigation systems were evaluated and four of the most viable systems were selected for simulation runs in the numerical model to predict the effect benefits and resources required for different operating scenarios for three lift locks with none, two and three water saving systems.

3 SCOPE OF WORK

According to the Terms of Reference (ToR) the scope of work is as follows:

1. Review and submit a written evaluation of the final reports for study SAA-74337. Review the salt water intrusion models, structure, methodology, programme logic, quantitative parameters, basic assumptions, data, formulas, calibration, simulation runs, and tools used to develop the studies based on descriptions of the models. Review and comment on the critical factors, non-quantitative parameters, criteria and variables affecting salinity intrusion based on review of the reports and discussions with its author(s). Review and comment on the conclusions, recommendations of the report and the consistency of results with other study data and results. Recommend modifications and improvements to models, methodology and assumptions to improve accuracy and consistency of results. State whether these recommended modifications warrant additional model runs and, if so, describe them.

2. Review and submit a written evaluation of the partial and draft final report for study SAA-135358. Review the mitigation of salt water intrusion models, mitigation systems, methodology and basic assumptions used to develop the studies based on descriptions of the models and discussions with the software developer. Review and comment on the critical factors, criteria and variables affecting salinity intrusion based on review of the reports and discussions with its author(s). Review and comment on the conclusions, recommendations of the report and the consistency of results with other study data and results. Recommend modifications and improvements to models and mitigation systems to improve accuracy and consistency of results. State whether these recommended modifications warrant additional model runs and, if so, describe them.

3. Identify and propose further studies and models to be carried out to better define the salt water intrusion problem and possible solutions. Describe critical variables to be defined, quantified, and interaction among them. Propose methodologies and tools that may be used for further studies. List possible providers to carry out these studies. List sources of information for further investigation. Estimate time, cost and resources required.

ACP has provided the following five documents to DHI for review:

Study SAA-74337	
Report A	*Salt Water Intrusion Analysis Panama Canal Locks, Existing Situation, Report A June 2003, Delft Hydraulics*
Report B	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Single Lift Locks, Report B September 2003, Delft Hydraulics*
Report C	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Three Lift Locks, Report C September 2003, Delft Hydraulics*
Report D	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Two Lift Locks, Report D September 2003, Delft Hydraulics*
Study SAA-135358	
Report F	*Salt Water Intrusion Analysis Panama Canal Locks, Future Situation: Post-Panamax Locks, Study, Modelling and Analysis of Salt water Intrusion Mitigation Systems for Revised 3-lift Lock Configurations, Report F April 2005, Delft Hydraulics.*

In addition, ACP arranged a three-day site visit on 22-24 June 2005 for two DHI delegates. The scope of work was discussed and the locks and canal facilities were visited.

A draft report of the study results was presented at ACP headquarters in Balboa 15 September 2005. Following the draft report, comments have been received from Delft Hydraulics (Tom Jongeling 13 September 2005) and ACP (21 September and 8 October 2005). The draft report has been revised to take the comments received into consideration.

4 REVIEW

4.1 Salt Water Intrusion Model

The simulation model is described in Chapter 5 of Report A. In Report F the simulation model is named Salt Water Intrusion in Locks (SWINLOCKS) model and in the following it will be referred to as SWINLOCKS.

SWINLOCKS is a box model. The model describes the flux of water and salt and takes into consideration the following parameters:

- Water level variations in the lakes and oceans
- Exchange of water volumes
- Ship Volume (if present in lock chamber)
- Salt concentration in locks, lakes and oceans

Salinity in SWINLOCKS is defined as volume averaged concentrations. SWINLOCKS consists of 28 boxes in total. Two boxes represent the oceans. The Gatun and Miraflores lakes each represent one box. An overview of the box configuration is shown in Figure 4.1 below. SWINLOCKS calculates the water balance taking into account the variation of the water levels in the lakes and overflows at the Gatun and Miraflores.

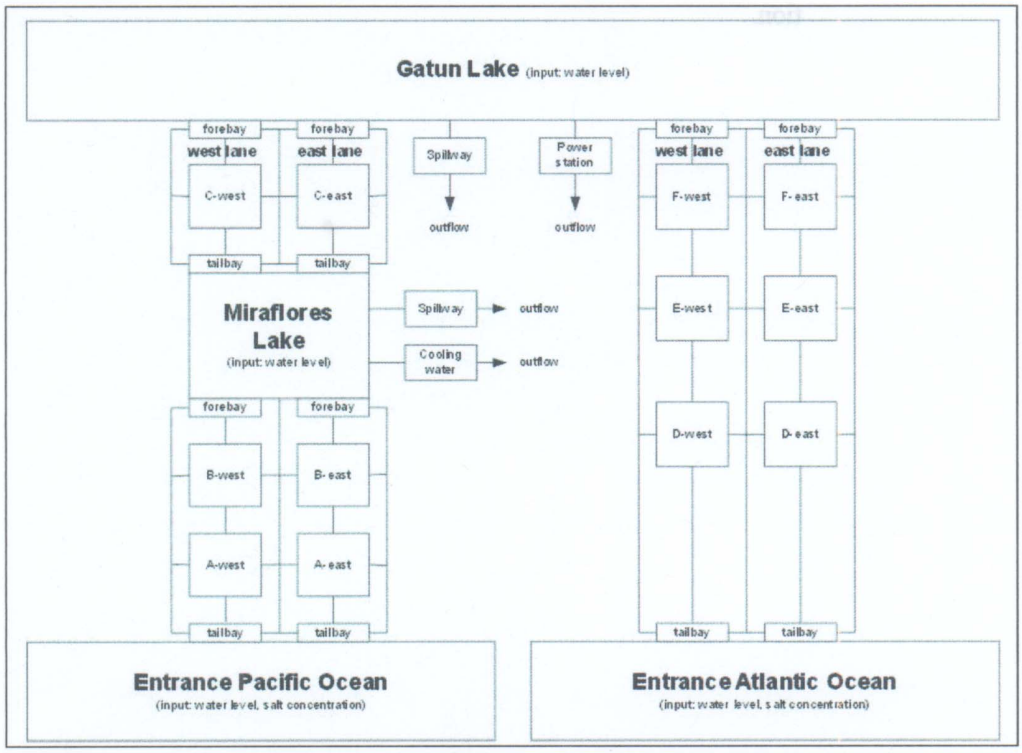

Figure 4.1 Overview of SWINLOCKS box configuration and input parameters, from Report A

The transport of salinity is described by the use of exchange coefficients. Distinctions are made between:

- Equalising of water levels/opening and movement of ship (also referred to as Step I and Step II)
- Down- and uplocking

The assumptions and equations are presented and explained in Report A, Chapter 5.

SWINLOCKS is well documented. All assumptions and equations are clearly presented in Report A. The methodology and scientific of SWINLOCKS are based on Dutch experience from water quality control at ship locks, Ref. /1/.

The concept of exchange coefficients for calculation of salt exchange is based on the use of volume averaged salinity values and known exchange of water volumes. This concept works when the volume averaged salinity is an appropriate approximation of the physics.

The salt exchange (SE) between the locks and basins is determined by an equation of the type:

Equalising of water levels and release over spillways

$$SE = e_x V_{ref} c$$

Opening of gates and movement of ship

$$SE = e_x V_{ref} (\Delta c) - (S c)$$

where e_x is the exchange coefficient, V_{ref} a reference volume, c the salt concentration corresponding to the reference volume, Δc the salinity difference between basins and S the submerged ship volume.

The exchange coefficient is in the case of ship movement dependent on the size of the ship relative to the reference volume according to the formula:

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

The exchange coefficient is an empirical constant that takes into account the following hydrodynamic processes:

- Mixing due to movement of ship
- Mixing due to ship propellers
- Mixing due to density flows (lock exchange)
- Stratification in locks
- Presence of sills in locks
- Opening time of gates at forebay and tailbay

By calculation of SE the exchange coefficient can be determined from the measured values of volume averaged salinity. The measurement campaign, wet-season and dry-season salinity measurements (November-December 2001, April 2002), was designed such to determine the exchange coefficients for each step in the equations. The exchange coefficients for each step in the lock operations have been assessed and determined based on the salinity measurements in the locks, forebays and tailbays. The calculated values of exchange coefficients for the measurements show a large scatter including unphysical values. This is most pronounced for the case of Step II movement of ship and density currents. One explanation for the scatter is the practical difficulties in making measurements with the presence of a ship in the locks. At the same time there are very strong salinity gradients in the locks aggravating the determination of a volume-averaged salinity. An analysis of the theoretical possible ranges of exchange coefficients has been prepared to limit the choice of exchange coefficients.

Comments: *SWINLOCKS is an empirical model where the exchange coefficients in the salt transport equations are determined from the field measurements.*

The large scatter in the values of the exchange coefficient is noticeable. In Report A, this is also acknowledged and sensitivity tests have been prepared.

The representation of the salt water intrusion by tailbay-locks-forebay by a box model approach is a reasonably and obvious choice. Salinity changes abruptly from basin to basin and one can keep track of the salinity and calculate the salt intrusion as it is done in SWINLOCKS. The complicated hydrodynamic processes within the locks can be parameterised by an empirical exchange coefficient. However, the presentation of the lakes (the Gatun Lake has an average volume of 5.17 km^3!) as one box is an important simplification of the system.

4.2 Salt Exchange through the Locks

In order to assess and understand the consequences of the basic assumptions and quantitative parameters, a simple model of the Gatun Locks has been prepared. This was done by implementing the SWINLOCKS formulas in a small MATLAB programme. Two cases with varying boundary conditions have been investigated: 1) Continuous uplocking from the Atlantic Ocean to the Gatun Lake 2) Continuous downlocking from the Gatun Lake to the Atlantic Ocean.

A ship with a length of 200 m, a draft of 10 m and a width of 30 m has been assumed. All exchange coefficients are set as in Report A (Tables 6.5 to 6.8).

Case 1) Uplocking. The salinity in the tailbay is set equal to 32 and 0 in the lake or forebay. The salinity in the forebay and in Lock E remains 0 throughout the simulation. By investigating the used exchange coefficients in Report A, Table 6.6, the exchange coefficient for ship movement for uplocking between Lock E and F and between Lock F and the forebay has been set equal to zero. The salt exchange is then due to movement of the ship volume only. In the case of uplocking the salt transport due to ship movement is downwards as the ship volume replenishes a water body from the upstream lock or forebay. If the salinity in the forebay initially is set to zero, as in this example, there is consequently no transport of salt into Lock F. See also Figure 4.2.

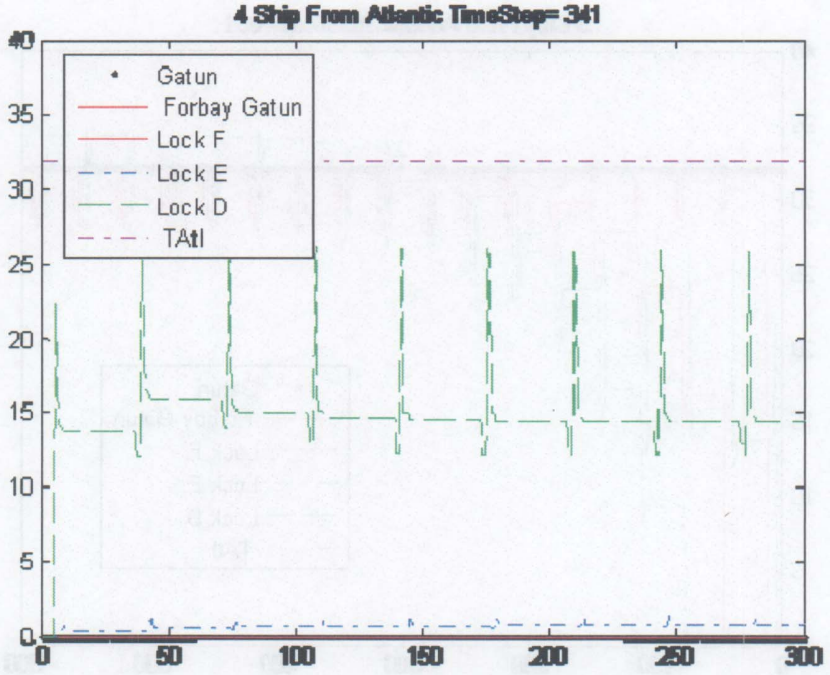

Figure 4.2 Simulation of uplockage Gatun Locks. Salinity shown as function of operation no

Comments: *SWINLOCKS predicts no salt intrusion for uplockage if the forebay salinity initially is zero.*

Case 2) Downlocking. As a test, the salinity in both the Gatun Lake and the Atlantic is put equal to 32. After some time salt concentrations above 32 are observed, see Figure 4.3. The reason for this is the application of an exchange coefficient for equalising water levels larger than 1. An exchange coefficient larger than one takes into account that there is stratification in the higher chamber and that withdrawal of the spilling water is located at the bottom of the upper chamber. However, as a side effect, this can create salinity as exemplified. Running the same simulation, but with all the exchange coefficients for equalising water, equals to 1. All salt concentration gradually moves towards 32 as expected.

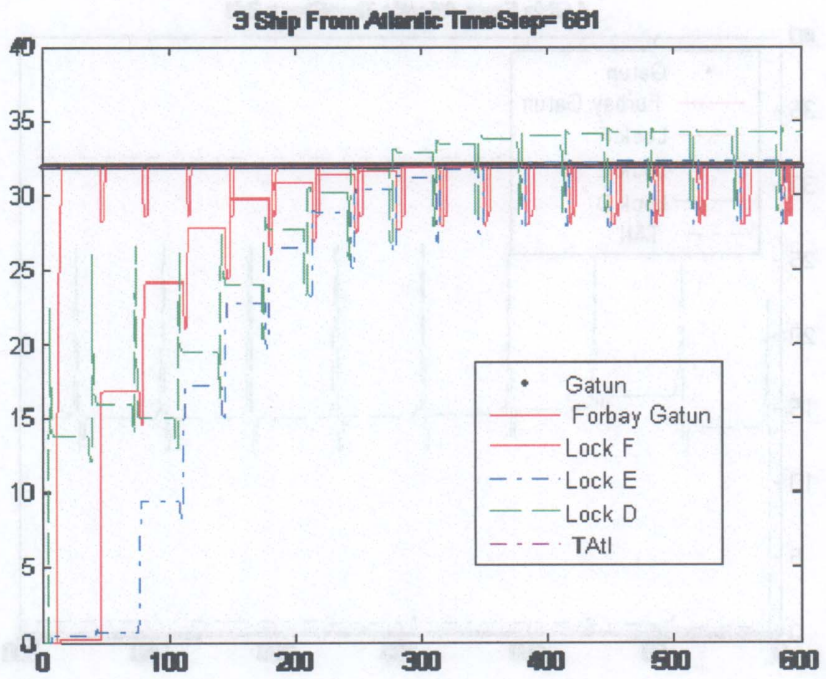

Figure 4.3 Development of salinity in locks if tailbay and forebay are equal to 32 ppt and the exchange coefficient is 1.2. Notice the generation of salt in Lock D

Comments: *Apparently it is possible to create unphysical salinity values. These unphysical values create artificial salinity gradients in the SWINLOCKS model*

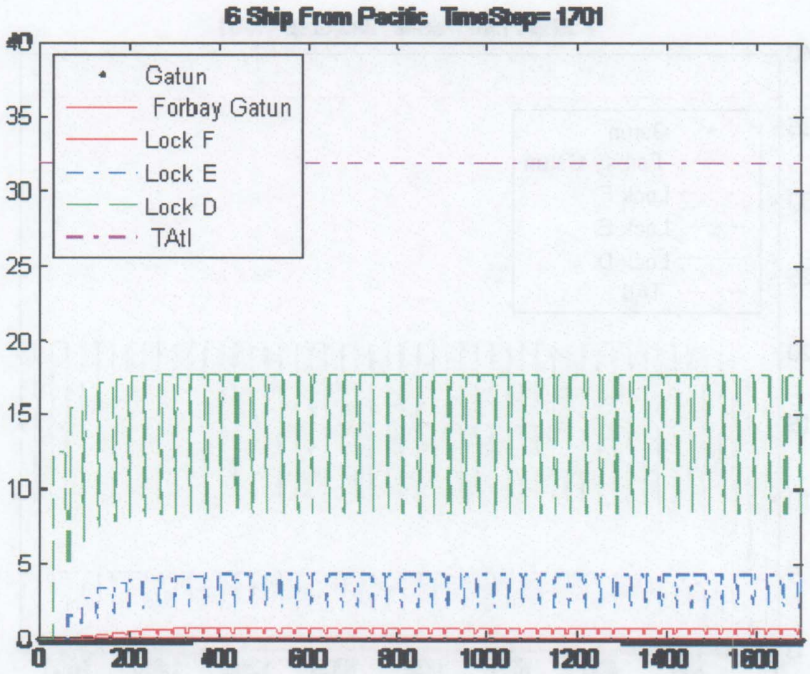

Figure 4.4 Continuously downlocking at the Atlantic side. Development of salinity in locks if Tailbay salinity is equal to 32 ppt and the Gatun Lake salinity is equal to 0 ppt

Figure 4.4 shows the development of salinity in the locks with continuously downlocking (in total 50 ships) at the Atlantic side. After downlocking of 10 ships, a dynamic equilibrium is reached. If the salinity in the tailbay is increased with 16% from 32 ppt to 37 ppt the salinity in all locks will be increased, and the salt transport from Lock F to the forebay is calculated to be 16% higher

Comments: *The salt transport varies approximately linearly with the salinity in the tailbay.*

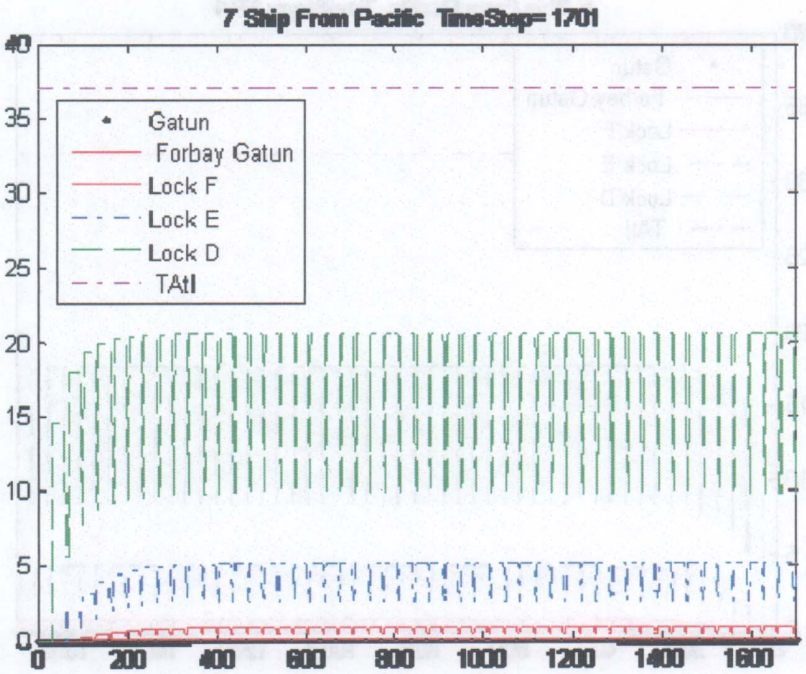

Figure 4.5 Downlocking at the Atlantic side. Development of salinity in the locks if the tailbay salinity is equal to 37 ppt and the Gatun Lake salinity is equal to 0 ppt

4.3 Boundary Conditions in Tailbays

In the tailbay of Miraflores Locks the temperature in the wet season is about 27-28 °C and during the dry season about 21 °C. The temperature in Miraflores Lake does not vary accordingly. The effect of a lower temperature on the density of sea water in the dry season is compensated for, see Report A, Chapter 5.6, by an increase in the salinity level in the dry season, using the relationships which exist between temperature, density and salinity. In the dry season the salinity in Miraflores Locks is measured to be 34 ppt. Table 5.8 Report A presents the salt concentration in the tailbays for each month. The salinity for the dry months of March and April has been increased to 37 ppt.

Comments: *The difference in temperature between wet and dry season is about 7-8 °C. This is equivalent to about 3 ppt. The dry season salinity has been increased by 3 ppt (from 34 to 37 ppt). However, an increase in density differences cannot be made equivalent by salinity without violating the boundary condition for the mass balance of salt. As shown in Section 4.2 the system is almost linear in the tailbay salt concentration. Accordingly, if the tailbay salinity is increased 9% (34 to 37 ppt) the salt import increases approximately by 9%.*

The boundary condition for water levels in the Pacific and the Atlantic Oceans follows the tide according to an approximation, see Report A, Chapter 5.6. For Miraflores Locks the tidal movement is, relative to PLD:

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

where A = 1.8 m, B= 0.575 m, $\omega_1 = (2\pi/44760)$, $\omega_2 = (2\pi/43233)$ and t is the time in seconds.

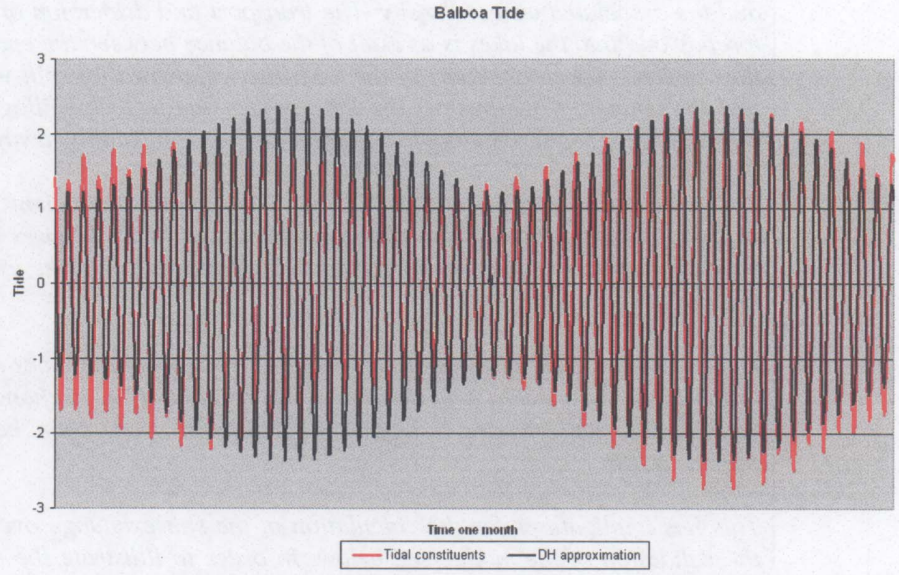

Figure 4.6 Comparison of the tidal approximation applied by DH (black line) and the standard tide (red line) in Balboa

Comments: *It is stated in Report A that a precise reproduction of the tide is not important considering longer time periods. However, it would have been appropriate to apply a tidal variation based on harmonic constants. In Figure 4.3 is shown a comparison between the approximation used and a variation based on standard harmonic constants (red line) for Balboa.*

4.4 Salt Exchange in the Forebay

In Report A, Chapter 5.4 the simulation of salt exchange in the forebay is explained. The water volume of the forebay in the Miraflores Lake and the Gatun Lake is defined as the surface area of the locks multiplied by the local water depth minus the sill at the entrance to the locks. This volume acts as a buffer between the lake and the locks. The time between lockages and dispersion of salt water due to density currents is accounted for by making the exchange coefficient time dependent.

Comments: *In the forebay and away from the locks the following hydraulic processes occur:*

- *Flow of water due to movement of ship volume*
- *Mixing due to ship propellers*
- *Flow due to withdrawal of spill water*

- *Density currents due to lock exchange at opening*
- *Density flow due to salinity differences with ambient water body*

These processes depend on the local geometry and water depths of the forebay as well as the surrounding water depths and determine the salt concentration in the forebay and the associated excess density. The transport and dispersion of salt away from the forebay and into the lakes is a result of the balance between the excess density induced flow towards the deeper part of the lake, the withdrawal of spill water in the forebay and the ambient flow towards the locks either due to lock spillage or over the spillways. As a consequence there is a gradual decrease in salinity away from the locks.

The representation of these processes by two exchange coefficients, one for equalising and one for gate opening and ship movement is difficult. Figures 6.1 to 6.4 Report A show that there is a significant scatter in the calculation of the exchange coefficients for the lock-lake situation.

Due to the presence of the density gradients away from the locks and the dependency of the local bathymetry, a more precise description of the exchange between the lake and forebay will require a higher resolution in space than has been applied in SWINLOCKS.

This has implications for the calculation of the salt exchange over the spillways and the validation of the model, see below. In order to illustrate the importance of these phenomena, a few 3D simulations of the salt exchange and flow in the vicinity of the Gatun Locks forebay and Gatun Spillway have been prepared.

In order to evaluate the flow and dispersion of salt in the vicinity of the Gatun Locks and forebay, a 3D model has been set up by application of DHI modelling tool MIKE 3 Flexible Mesh (FM) for simulation of 3D free surface flow. The model area is shown in Figure 4.7 and covers an area of approximately 2x2 km^2 including the Gatun spillway. The horizontal simulation mesh varies between 25 to 75 m and 10 vertical layers have been applied.

For the sake of illustration, the lock operation is assumed to be a sequence of downlockage during the afternoon followed by uplockage during the following morning. A period of one and a half day has been simulated. The following conditions have been applied:

- Lock operation, 36 Panamax ships per day (18 uplockings and 18 downlockings)
- Opening and movement of ship. Downlocking: Influx of salt from Lock F and into the forebay occurs as a pulse of salt water with a volume corresponding to a Panamax ship volume of 90,000 m^3 followed by a spillage (outflow) of 95,000 m^3. Uplocking: Outflux of a volume of water corresponding to 90,000 m^3 with a salinity equal to the forebay followed by a spill volume of 95,000 m^3. During the night it is assumed that the locks are closed
- Gatun spillway. Dry season (1.8 m^3/sec)
- Salinity in Lock F. A constant value 0.5 ppt has been applied

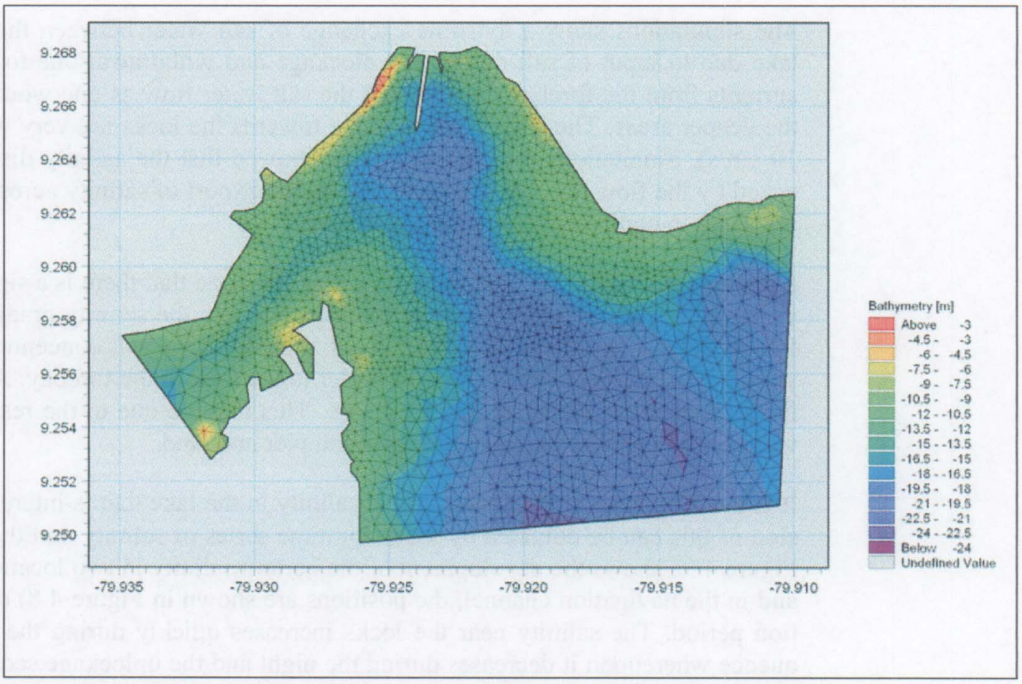

Figure 4.7 MIKE 3 FM model bathymetry. Water depths are taken from the digital sea-chart Cmap

In Figure 4.8 is shown an example of the dispersion of salt in the dry season after one and a half day of simulation.

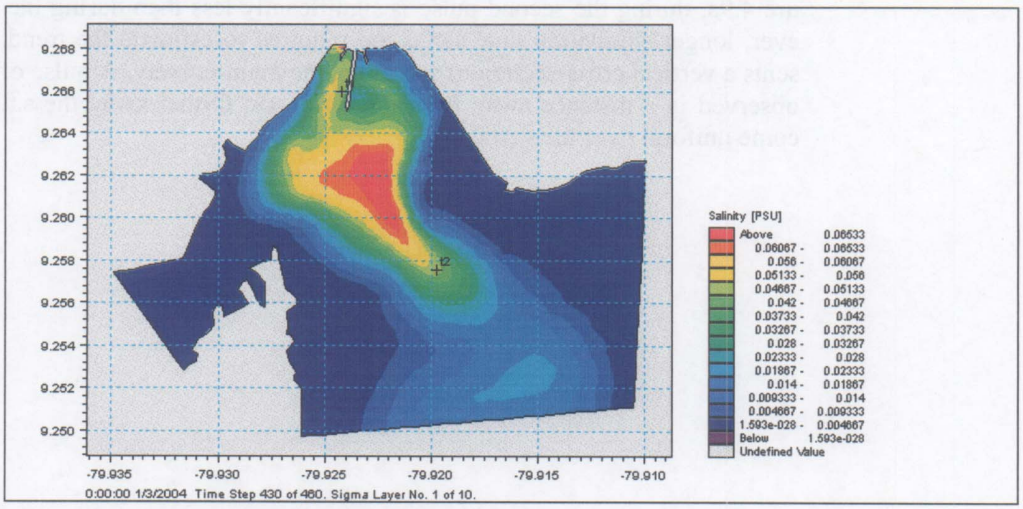

Figure 4.8 Dry season. Near bed salt concentrations after one and a half day of simulation. PSU (Practical Salinity Unit) is equal to ppt. t1 and t2 indicates the position of time series shown in Figure 4.9a

The simulations show a dynamic exchange of salt water between the forebay and the lake due to input of salt during downlockage and withdrawal due to spillage. Density currents from the forebay develop and the salt water flow as one would expect towards the deeper areas. The currents in the lake towards the locks are very weak (less than 4-10 cm/s). Simulations for the wet season showed that the salinity distribution is influenced by the flow towards the spillway and the export of salinity across Gatun Spillway increases in comparison with the dry season.

Although the results are only indicative they illustrate that there is a significant variation in the salinity in the vicinity of the forebays and that the salinity gradient is significant. In particular it is noticed that there is a difference in the salt concentration between the west and the east side of the approach pier to the lock in the forebay. Apparently the salinity tends to be higher on the west side. This may be due to the restriction of the divergence of the flow between the approach pier and land.

It is the long-term development of the salinity in the lake that is interesting. An impression of this can be obtained by assessing time series of salinity and the vertical mixing. Figure 4.9a shows the development of the bottom salinity in two locations (Gatun Locks and in the navigation channel, the positions are shown in Figure 4.8) during the simulation period. The salinity near the locks increases quickly during the downlockage sequence whereupon it decreases during the night and the uplockage sequence the following morning, whereupon it increases again during downlockage. Away from the locks the salinity variation is more slow and the salinity increases after some time. The salt input during downlockage gradually moves towards the lake and decreases as a result of dilution. The flow towards the locks during uplockage counteracts the spreading of salt into the lake. It is noticed that the increase in salinity in the navigation channel, see Figure 4.9a, during the second pulse is significantly less than during the first pulse. However, longer simulation time series are required to estimate the trend. Figure 4.9b presents a vertical cross-section of salt along the main fairway. A pulse of salt water can be observed in a distance away from the locks and further away the salinity tends to become uniform over the vertical.

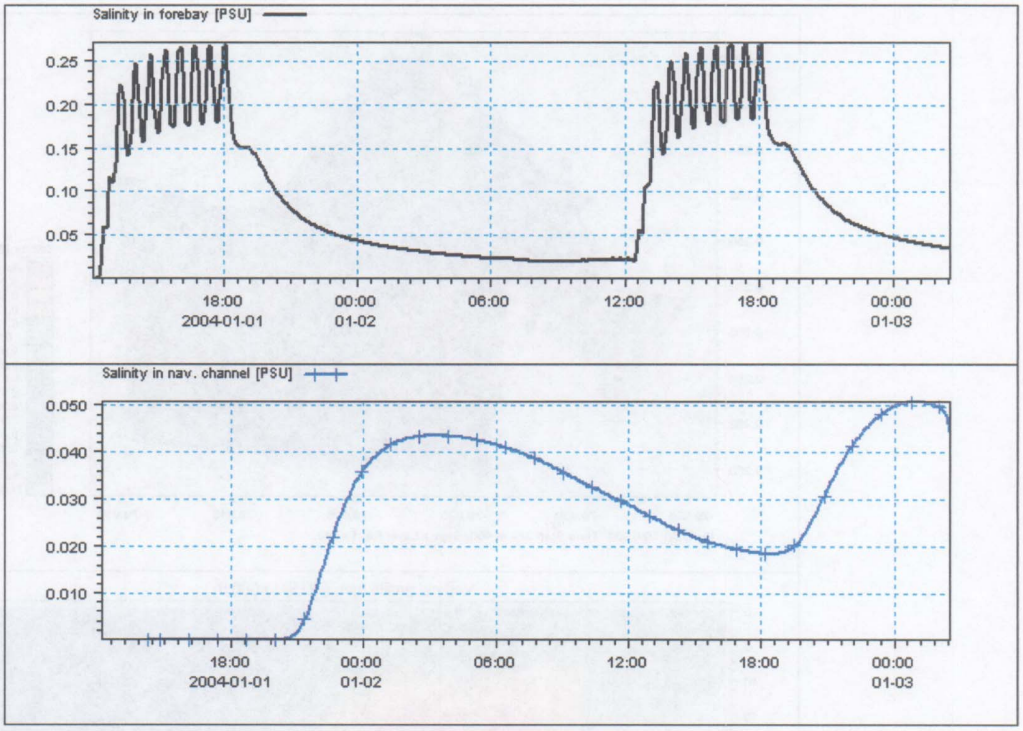

Figure 4.9a Time series of salinity in bottom layer at Gatun Locks (t1) and the navigation channel (t2). The positions are shown in Figure 4.8

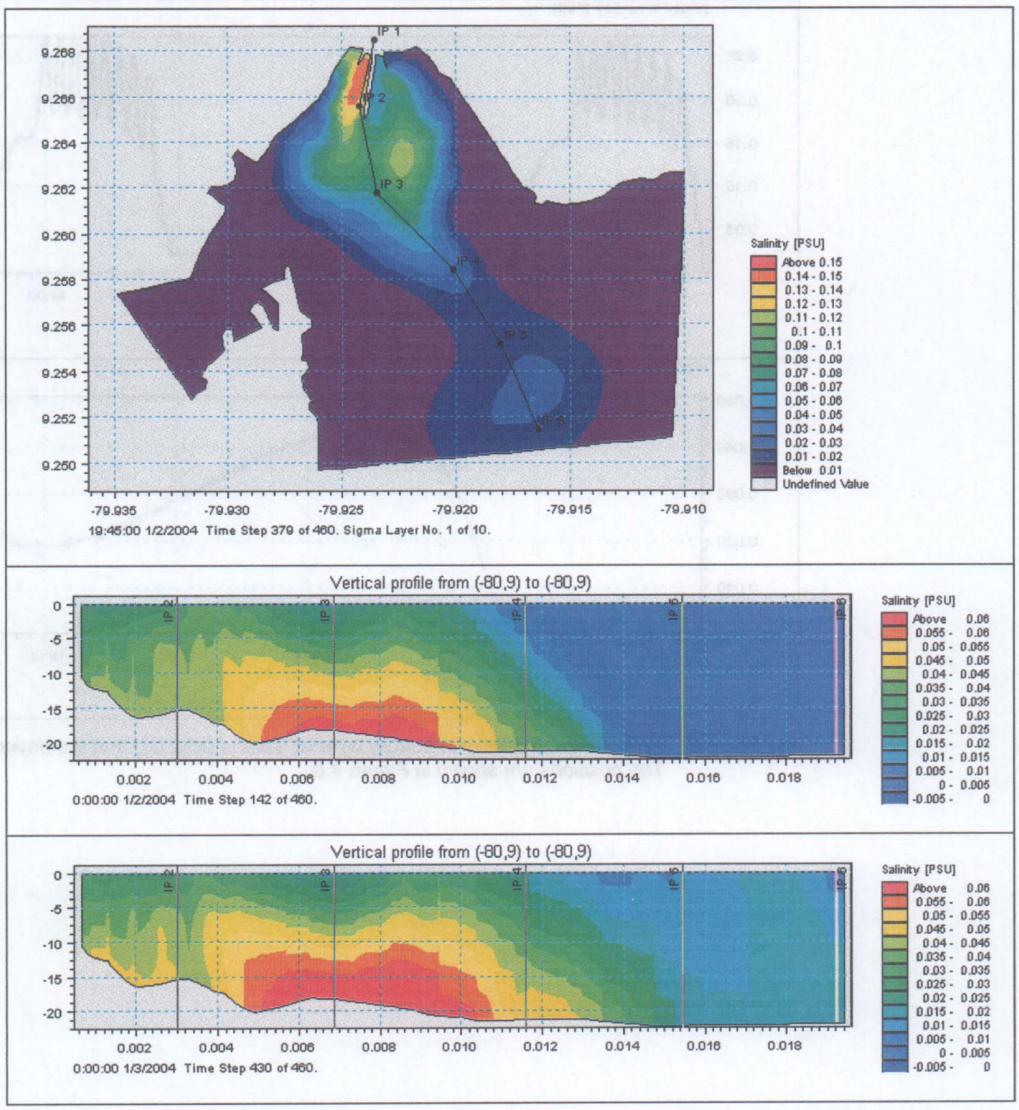

Figure 4.9b Vertical transect of salinity along the main navigation channel, see upper panel after the first downlockage sequence (12 hours simulation) and after the second sequence (36 hours simulation). PSU is equal to ppt

Comments: *The simulations indicate that over a certain time period a steady but seasonally varying salinity distribution develops near the locks. The dynamic equilibrium between the input of salt through the locks and export of salt with the spill water and over the spillway determines the salt distribution.*

It should be emphasised that the presented results are preliminary. In reality mixing due to wind, heat exchange and ship movements will enhance mixing and thereby influence the distribution of salinity. Persistent wind forcing will also influence the salinity distribution. Longer simulation periods (order of one month) must be prepared to

consolidate the observations.

SWINLOCKS calculates the volume averaged salt concentration in Gatun Lake. In reality the salt concentration varies throughout the lake. Higher salt concentrations will occur close to the locks and lower away from the locks. The 3D simulations over a period of 2 days indicate that SWINLOCKS may over predict the salt water intrusion into the lake. SWINLOCKS may underestimate the salt transport out of the lake through the gates. By simulating a longer period in space and time in 3D it should be possibly to quantify this further, reference is made to Section 5.

4.5 Salt Exchange across Spillways

As explained above the salt export from the lakes over the spillways is calculated from an exchange coefficient proportional to the spillway volume and the salt concentration in the lake.

For Miraflores Lake the volume averaged salinity is 1.5 ppt and 0.7 ppt in the dry and wet season, respectively. In order to achieve these values, the exchange coefficient was determined to be 1.5. This means that the average salt concentration of the water, which flows away over the spillway, is 1.5 times the volume-averaged salinity. By comparing with Table 3.4 in Report A one sees that the salt concentration in the forebay of Miraflores Locks is approximately 1.5 times the average salt concentration in this lake.

The volume average salinity values in the Gatun Lake could not be measured. The salinity values were below the accuracy of the applied instruments of 0.1 ppt. In the vicinity of the locks a salt concentration up to 0.2 ppt was observed during the dry season. Based on a sensitivity analysis, an exchange coefficient of 7.5 was chosen, see also Report A, Chapter 6, Table 6.15. From Table 6.15 it can be seen that volume averaged salinity in the Gatun Lake is the exchange coefficient divided by the salt concentration near the Gatun Dam. This says that the water spilled at the Gatun Dam has the same salinity as in the forebay of the Gatun Locks.

Comments: *Firstly, it does not seem plausible that the salinity at the spillway is equal to the salinity in the Forebay. Secondly, the salinity in the lake must decrease with increasing distance from the locks. 3D simulations for the Gatun Lake and Forebay demonstrate this above.*

4.6 Gaillard Cut

In Report A it is discussed whether salt can penetrate to the Gatun Lake along the bottom of Gaillard Cut. Very low salinity values are measured in the Cut and in the forebay of Pedro Miquel Locks. According to Table 3.4, the salinity is at maximum 0.1 ppt. This corresponds to a lock exchange flow of approximately 0.05 m/s (front velocity).

However, the question is whether any stratification will be able to exist in the narrow Cut with the intense traffic and mixing produced by ships. The following conservative estimate can be made:

According to Ref. /2/ about 1 per cent of the ship propulsion energy is available for mixing the water column. It is assumed that per ship lockage a water volume equal to

the lock is forming a lower layer with an excess density equivalent to 0.1 ppt and that the water depth is 20 m. The energy required to mix this lower layer over the vertical is equal to about 1.5 MJ per ship (assuming conservatively that an amount of water equal to the lock volume with a density equivalent to 0.1 ppt follows the ship). The propulsion energy required to sail through Gaillard will depend on the size of the ship. If we assume a small ship with a propulsion energy of say 5000 kW and further assumes that it takes one hour to sail through the Cut the energy available for mixing becomes 180 MJ.

This shows that if any stratified flow occurs in the Cut, the water lower layer will be mixed up in the upper layer by ship propeller actions. As a consequence, the salt will be carried back to the lock with the spill water.

4.7 Testing and Validation

The testing and validation of SWINLOCKS is presented in Report A, Chapter 6. This was done by determining the exchange coefficient for outflow of salt over the spillways in the Gatun and Miraflores locks such that the simulation results over one year give the correctly measured salinity variation.

Comments: *Within mathematical modelling one distinguishes between model calibration and validation. Measured data for one particular period in time is used to calibrate and test the model until there is an acceptable agreement between observations and model results for a specific set of model parameters. Simulating another set of measured data without changing the model parameters and verifying that the simulation and observations remain in agreement then does validation of the model.*

The salt measurements in the locks have been designed and applied to determine the exchange coefficients. This implies that the model calculates the measured salt concentrations given in the exchange coefficients. Provided that the volume averaged salinity in the Gatun Lake is less than 0.1 ppt and not higher than 0.2 ppt near the Gatun Locks, the exchange coefficient for salt over the Gatun spillway is estimated to be 7.5.

From a modelling point of view SWINLOCKS is calibrated by tuning the exchange coefficients for salt export over the Gatun Lake spillway to reproduce the yearly variation within a band of 0.1 to 0.2 ppt. In the locks the exchange coefficients have been determined from the measurements.

A validation requires reproduction of an independent set of salinity measurements.

4.8 Measurements

The field data collection is described in Report A, Section 3. Two data collection programmes were undertaken, one in the wet season (week 48-50, 2001) and one in the dry season (week 15-16, 2002). The dry season programme was revised based on the experience of the first campaign. As mentioned above, the objectives of the measurements were to understand the saltwater intrusion processes and provide salinity data to determine the exchange coefficients in the simulation model. The planning, data collection and co-ordination with the calibration of SWINLOCKS are well documented.

The salinity measurements were made with two fast response CTD instruments (Conductivity, Temperature and Depth) (Report A, Section 3.2.4). The accuracy of the instrument applied for salinity profiling is 0.01 ppt with a lower limit of 0.1 ppt. The accuracy of the instrument applied in a fixed position is 0.1 ppt with a lower limit of 0.1 ppt.

Comments: *The applied CTD instrumentation is applicable for normal salinity ranges as they exist from the tailbay and up into the locks. However, the lower limit of the instruments (0.1 ppt) is problematic for the measurements in the forebays at Pedro Miquel, Gatun, Gaillard Cut and in the Gatun Lake. The measurement of the very low values in the wet season could have been used to revise the second campaign in the dry season.*

It is recognised that measurements of salinity are very difficult in the forebays at Pedro Miquel, Gatun, Gaillard Cut and in the Gatun Lake due to the very low values that are below the limit of standard CTD instruments. The observed values are well below the usual fresh water limit of 0.4-0.5 ppt.

The psu (or ppt) value of distilled water is defined as zero. Fresh tap water with zero salinity has a very small psu value due to other dissolved salts. Zero-salinity measurements were therefore made each day prior to field data collection by placing the instrument in tap water and measure the corresponding ppt value. The salinity values, which were measured in the lakes and in the upper locks, have been corrected with these zero values.

Comments: *In view of the very low salinity values the CTD's should have been adjusted to zero in distilled water. Chemical analysis of water samples in the lakes should have been prepared and the cloridity contents and other dissolved salts determined. Chemical analyses of the tap water would make it possible to determine if this water could be used to define the level of the CTD instrument.*

Electrical conductivity of fresh water (for example groundwater) is generally measured with field conductivity meters equipped with a suitable conductivity and temperature sensor designed for this purpose. The range will depend upon the selected sensor and the meter; but can for most conductivity meters be from fresh to brackish and saline water. Lower conductivity can easily be measured with adequate meters and sensors.

The conductivity meter can be used with off factory sensor constants (calibration factor). It should be calibrated at regular intervals. The sensor constant is for example measured for a 0.01 N standard KCl solution with a conductivity of 141.3 mS/M at 25°C and the meter calibrated against the measured value. During field measurements, the instrument must be checked with another standard KCl solution of a salinity close to that of the water samples to be measured.

In fresh or nearly freshwater the conductivity is influenced by other dissolved salt ions (Ca, Mg, S etc.) as well as Chloride. It is therefore important to prepare standard chemical water analysis of selected samples and identify the salts responsible for the measured conductivity.

The variation of the salinity in the vicinity of the forebay, towards the deeper parts of for example Gatun Lake and the spillways are important for the understanding of the saltwater balance of the Gatun Lake. For that purpose profiles were measured along the main shipping lane, in the deeper area east of the Gatun Locks and near the Gatun spillway.

Comments: *In view of the importance of the salinity variation in the area near the Gatun forebay and spillway, please refer to the discussion concerning the exchange coefficient for the Gatun spillway above, more salinity data in this area would have been important to limit uncertainties.*

4.9 Water Saving Basins

The following discussion is based on Report B single lift lock system but is also valid for two and three lift lock systems. In the SWINLOCKS model the water saving basins (WSB) are lumped together as one water volume with an average salt concentration in the basins (see for example Report B, Section 3.2).

Figure 4.9 and Figure 4.10 below show in principle how a water saving basin system consisting of 6 basins is filled and emptied. This situation is evaluated in the following.

It is noted that the water balance is correct formulated for both lock filling and lock emptying.

4.9.1 Salt Balance Empty WSB

When the locks are filled with water from the WSB, all salt from the WSB will be transported into the lock. This will result in an exchange coefficient for emptying WSB equal to 1.00, as listed in for example Tables 5.1 and 5.2, Report B.

In Report B (page 5.1 lower part) is presented one test case, where the salinity is 10 ppt in the lowest WSB increasing to 20 ppt in the highest WSB. The time variation of the average salt concentration in the lock can be calculated by hand confirming the results shown in Figures 5.1 and 5.2, Report B.

On page 5.2 Report B is written "…. The results become rather uniform at the end of the filling (but the highest concentration is present at the floor)".

Comments: *The analysis seems valid and the conclusion " From this we conclude that the six WSBs can be replaced by a single WSB provided that the salt exchange coefficients are selected well" from page 5.2 Report B is correct.*

4.9.2 Salt Balance Fill WSB

The amount of salt that is filled into the locks depends on the salt concentration profile in the lock, and the location of outlets from the lock.

The amount of salt transported from the lock to the WSB is given (see for example Report B, page 4-16).

$e_{wsbfill} V_{save} C_{lock}$,

$e_{wsbfill}$ Exchange coefficient

V_{save} Water volume in the water saving basins

C_{lock} Average salt concentration in the lock

An exchange coefficient higher than 1.00 has been applied. The coefficient is taken equal to $e_{wsbfill} = 1.25$ (Table 5.1, Report B) for uplockage and $e_{wsbfill} = 1.10$ (Table 5.2, Report B) for downlockage. The main reason for the difference is that at downlockage a ship is present in the lock, whereas at uplockage no ship is present in the lock.

The lock is gradually filled with water from the bottom of the lock into the WSB. First the upper WSB is filled, see Figure 4.10, the yellow volume. The largest salt concentration will be found in the upper WSB. In this case the coefficient $e_{wsbfill}$ will be larger than 1.00 (meaning that the average salt concentration in the WSB becomes larger than the average salt concentration in the lock).

In Report B (page 5.3 upper part) is written: "When we compute the quantity of salt that is transferred successively to the upper WSB, intermediate WSBs and lower WSB, we find that these quantities rather well correspond to the quantities of salt that were present in the respective lower water layers in the chamber". This corresponds to the situation shown in principle in Figure 4.10. The finding is not supported by any figures in the report.

Comments: *As the water is withdrawn from the lock through a large number of holes in the bottom of the lock, this seems a valid observation.*

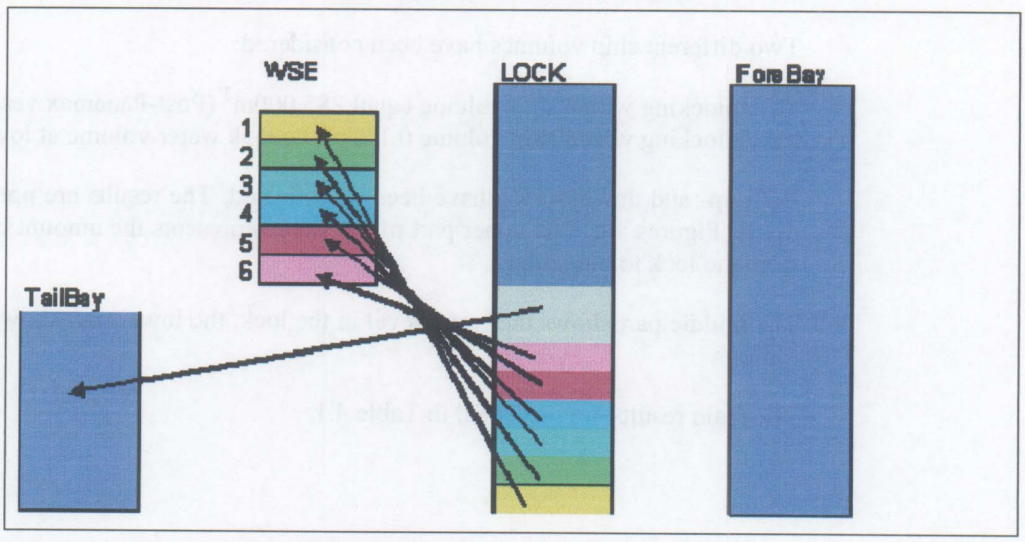

Figure 4.9 Principle emptying lock (at the bottom), filling WSB and Tailbay

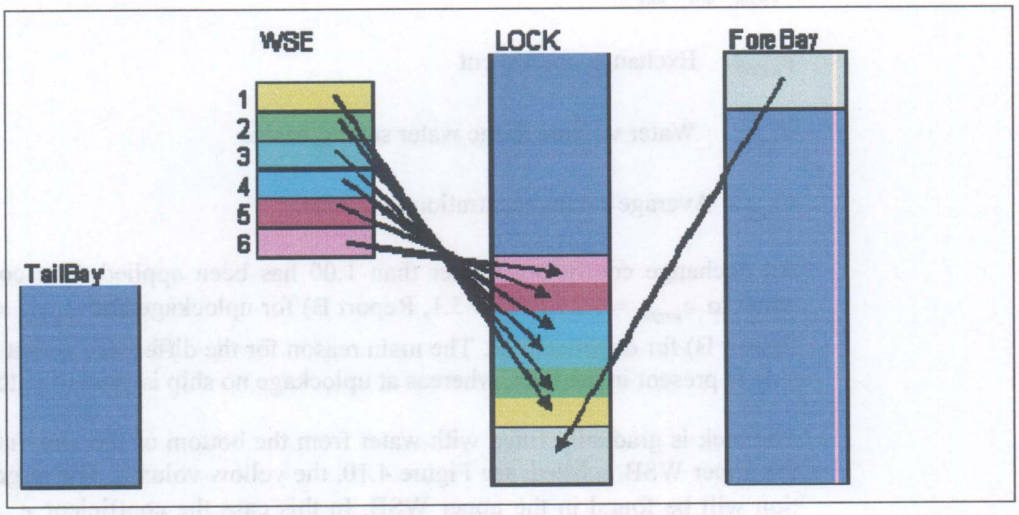

Figure 4.10 Principle filling lock (at the bottom) from WSB and forebay

4.9.3 Evaluation of WSB and Exchange Coefficients

In order to evaluate the effect of the WSBs on the salt transport from the tailbay to the forebay, a simple salt exchange model has been set-up for a single lift.

The model is based on the formulas taken from Report B page 4-4 to page 4-20 and the exchange coefficients listed in Tables 5.1 and 5.2 in Report B. The following assumptions have been made.

1. The salt concentration at the forebay has been put equal to zero
2. The water level in the tailbay has been set equal to 27 m
3. The salt concentration at the tailbay has been set to equal 32 ppt
4. The water level at the tailbay has been set to equal 0 m

Two different ship volumes have been considered:

a) Uplocking with a ship volume equal 285.000m^3 (Post-Panamax vessel class VIII)
b) Uplocking with a ship volume 0.1% of the lock water volume at low level

Both up- and downlocking have been investigated. The results are presented in Appendix A, Figures a-d. The upper part of the figures presents the amount of salt transported from the lock to the tailbay.

The middle part shows the water level in the lock, the lower part shows the salt concentrations.

The main results are presented in Table 4.1.

Table 4.1 Relative amount of salt per ship compared with the situation with no ship (column no. 1, 100%) transported into the forebay

	No Ship Vol 0 m^3	Ship Vol 40,000 m^3	Ship Vol 285,000 m^3
Uplocking	100%	70%	12%
Downlocking	100%	127%	564%

The following can be seen:

1. The figures and the table clearly show that the largest amount of salt transported into the forebay occurs at downlocking with large vessels.

2. At uplocking the amount of salt transported into the forebay is larger for a small ship than for a big ship. At uplocking the ship movement induces a flow of water into the lock that reduces the outflow of saltwater.

3. When a Post-Panamax vessel is present almost 50 times more salt is transported into the forebay at downlocking compared to uplocking. This is mainly because at downlocking the ship movements result in water movement from the lock to the forebay, while the opposite is the case at downlocking.

A sensitivity analysis of the salt transport has been prepared by increasing the exchange coefficients by 10%. The results are shown in Table 4.2. From the table is can be seen the salt transport is only weakly dependent on the exchange coefficients.

Table 4.2 Sensitivity analysis exchange coefficients, single lift lock: the amount of salt (per ship) transported into the forebay. Uplocking, ship Vol 320,000 m^3

	Exchange coefficients Report B Table 5.2	+10%	Change
Filling WSB	1.1	1.21	3%
Empty lock to tailbay	1.1	1.21	-2%
Move ship from forebay	0.15	0.165	2%
Open tailbay gate	0.4	0.44	1%

Comments: *The results for a single lift lock system are consistent and not sensitive to the value of the exchange coefficient.*

4.9.4 Reducing the Ship Volume

By decreasing the relative ship volume by 10% from 285,000 m^3 to 257,000 m^3 the amount of salt transported into the forebay at downlocking will be reduced by approximately 10%

Comments:. *Comparing the result for a single lift lock with the existing locks, a single lift system with WSB will increase the salt transport more than one decade.*

4.9.5 Reducing the Number of WSBs

If the number of water saving basins is reduced from 6 to 3 the salt transport is reduced by 12%. It shall be noted that if the number of WSBs is reduced from 6 to 3 the amount of water to be used for the downlocking increases by 60% (from 0.25 to 0.4 times the water volume without WSB).

It is noted that a single lift system gives approximately an order of magnitude higher salt transport than a three-lift system.

> ***Comments:*** *The analysis of the single, double and three lift lock system and application of WSBs is correct.*

4.10 Exchange Coefficients for Post-Panamax Locks

In order to evaluate the impact of the Post-Panamax Locks it is important that the exchange coefficients applied in SWINLOCKS take the new lock configurations into account. One aspect of this is the application of WSBs as discussed above.

The exchange coefficients for the new lane (3 lift system) are presented in Report C (Tables 5.1 uplockage and 5.2 downlockage). Comparing these exchange coefficients with the exchange coefficients used for the existing lanes (Report A, Tables 6.5, 6.6, 6.7 and 6.8) one sees that the new lane exchange coefficients for a) moving ships between b) equalize water levels are almost identical with the existing lane.

Delft3D simulations have been applied to evaluate the conditions in the Post-Panamax Locks. By combining the results of the Delft3D with the experience from the existing locks the exchange coefficients have been defined. This gives, Report C Section 5, for the three lift lock system (that causes the least salt intrusion) that the exchange coefficients are set equal to the existing locks. Consequently, in comparison with the existing locks, Post-Panamax Locks cause an increase in salt exchange due to the larger size of ships and use of WSB, only.

The exchange coefficient between the Gatun forebay and lake is also set equal to the value for the existing lanes.

> ***Comments:*** *As discussed previously the salt exchange from one lock to the next is not very sensitive to value of the exchange coefficients. The salt transport through the Post Panamax Locks must therefore be expected to be adequately described.*
>
> *The exchange coefficient between the forebay and the lake depends, as discussed in Section 4.4 above, also on the local water depths and the geometry of the forebay. As the net input of salt to the lake is the result of the difference between in- and outflux of salt this deserves more attention.*

4.11 Mitigation Schemes

Report F describes the investigation of mitigation schemes. The following mitigation systems have been considered and evaluated:

1. Stepwise flushing of all lock chambers (dummy lockage)
2. Flushing of middle and upper lock chamber
3. Flushing of upper and lower lock chamber
4. Enhanced flushing of upper and lower lock chamber
5. Intensive flushing of upper lock chamber
6. Exchange of salt water with fresh water in lower lock chamber
7. Drainage of salt tongue through slit in forebay bottom

8. Flushing of salt water from pit in forebay
9. Flushing of salt water from pit with perforated floor in forebay
10. Pneumatic barrier at the entrance to the lower lock

In consultation with ACP, mitigation systems 1, 2, 9 and 10 were investigated in depth. An assessment of the exchange coefficient gives that these must be most difficult to determine for the mitigation systems 9 and 10. For mitigation systems 1 and 2 already established exchange coefficients can be applied.

System 9. Flushing of salt water from pit with perforated floor in forebay. Delft3D simulations in a 2D vertical section have been applied to determine the exchange coefficient. The salinity in the upper lock is set equal to 2 ppt and the lake salinity is zero. The vertical layout and ship movement varied.

Comments: *In the forebay the flow is highly three-dimensional due to divergence and convergence of the flow. The movement of the ship will push water laterally. The hydrodynamics in the forebay cannot be described in a 2DV model.*

A critical point for the efficiency of the pit is the entrainment of salt up into the water column thereby reducing the salt drainage. The entrainment is dependent on the density gradient across the interface. The higher density gradient the smaller the rate of entrainment. The application of a value of 2 ppt in the upper lock may provide too optimistic values for the efficiency of the pit. It is noted that salt values in the upper lock are as low as 0.2 ppt. The absolute amount of salt that penetrates into the forebay may be less for a lock salinity of 0.2 pp. However, the amount of water required to drain it through the pit may become higher because it will be mixed up in a larger water body.

System 10. Pneumatic barrier at the entrance to the lower lock. It is assumed that the pneumatic barrier is "well designed" and hinders the salt exchange due to density differences. However, salt exchange due to movement of ship volume is not affected.

Comments: *As pointed out in Report F, pneumatic barriers have not been applied for as deep waters (17-20 m) as in the tailbays of the Panama Canal but only up to 15 m. If this mitigation system is selected, further studies must be conducted to assure the functionality as proposed in Report F.*

In all 10 mitigation schemes have been considered. These schemes are based on an extensive survey of engineering state of the art and must be considered complete.

Comments: *The analysis presented in Report F of mitigation schemes must be considered complete.*

Apart from what is specifically analysed it could be investigated if the closure of tailbay gates as soon as possible after ship movement at downlocking could help to minimise mixing between tailbay and first lock. This could further be investigated for forebay upper lock also. The shorter the gates are open the less mixing and salt exchange will occur.

Emergency gates installed at the upstream end of the locks could serve as a saltwater mitigation measure by closing them after downlocking of ship has passed and is entering the upper lock chamber. For the Post-Panamax, this could be achieved if the emer-

gency gates can be designed to open and close in presence of water flow and a differential pressure head.

Overall the application of a salt pit is a feasible and attractive mitigation measure. A 3D hydrodynamic analysis of the water exchange in the forebay and the design of the salt pit in order to minimise salt intrusion is recommended.

5 FURTHER STUDIES

This section describes further studies to be carried out to better define the salt water intrusion problem and possible solutions.

5.1 Analysis of Salt Exchange between Upper Lock and Lakes

Objective

- To better understand the flow and salt exchange in the vicinity of the locks as a prerequisite to further investigations
- To determine the short-term (couple of days) net exchange of salt between the upper lock, forebay and the surrounding water body
- To identify the salinity gradients and their variation in the vicinity of the locks.

This must be prepared for both Gatun and Pedro Miquel forebays.

Methodology

Set up and calibrate a 3D hydrodynamic model of the forebay and lake. The 3D model must resolve the flow in the upper lock, forebay and describe the intrusion of salt from the upper locks as well as flow over the spillway (for Gatun lake) and a relevant portion of the lake. The model must be able to include mixing due to winds, heat exchange, and ship movements. The movement of a ship into the first lock must also be included. The model must be applied for both dry and wet season.

Results

Computed salinity maps and gradients in the vicinity of the locks. Water movements, transport and residence time of water bodies. The results should be applied to plan a dedicated measurement programme.

5.2 Determination of Long Term Salt Concentration in Lakes

Objective

To determine the long-term salt concentration in the lakes (time scale years-decades).

Methodology

Combine 3D model and lock model simulations to determine the long-term salt concentration in the lakes (time scale years) after construction of Post-Panamax locks. A procedure for such a combination is not simple to establish, because: the salinity close to the locks varies with each down- and uplocking, whereas far from the locks the variation is much slower with a time scale of month to years. To determine the long-term salt concentration it requires that both time scales are resolved in the model.

An approach could be as follows: Firstly a Lock-model will be applied to simulate the salt in- and outflow for daily up- and downlocking sequences for a range of salt concentrations in the lake. Secondly a 3D model will be applied. For inflow of salt the salinity

value as calculated by the lock model can be used as boundary condition for the 3D model. For outflow of salt the salinity is determined by the results of the 3D model. This salinity is entered into the lock model and the next lock sequence can be computed and so forth.

It is expected that the amount of salt transported into the lake is only weakly dependent on the salt concentration in the lake near the lock. Whereas the amount of salt transported out from the lake is expected to be more or less proportional with the amount of salt in the lake near the locks. This assumptions needs to be verified.

Results
Long-term salt input to lakes and salinity distribution.

5.3 Salinity Measurements and Salt Intrusion

Objective
To support the establishment and validation of a 3D forebay model (Sections 5.1 and 5.2) and enhance the understanding of salt exchange through the locks and into the lock.

Methodology
Conduct a series of high precision salinity measurements consisting of:

- Salinity transect measurements perpendicular to the coast at wet and dry season.
- Continuous salinity measurements at selected fixed positions, for example in upper lock, forebay and outer forebay, Gatun spillway and a position some distance away
- Design and location of measurements shall be prepared based on 3D model results to optimise information
- Prepare a Rhodamine Tracer (or other) experiment to measure in situ dilution from lock, to forebay to lake. Rhodamine can be measured at even very low concentrations and will be a unique tracer for the fate of the water body through the locks and into the lake.

Results
Measured salinity maps and gradients in the vicinity of the locks to validate 3D model. Dilution and fate of a water body from injection in for example tailbay to the lake (Rhodamine experiment).

Notes
Salinity values are very low, less than say 0.2 ppt. DHI recommends to apply for example Seabird 19plus that can measure salinity in freshwater with an accuracy of 0.1 ppm. Water samples of lake water at low salinity must be chemically analysed and a correlation between Chloride and conductivity established.

See also:

http://www.seabird.com/products/spec_sheets/19plusdata.htm

So-called Rhodamine Water Tracer (WT) is recommended. This is a harmless fluorescent tracer that can be detected at very high accuracy by a turbidity sensor. Unlike Rhodamine B it does not attach to suspended sediments. Care must be taken that the Rhodamine dilution before injection has a density equal to the water body it shall trace.

Further information about Rhodamine WT can be found for example at:

http://smig.usgs.gov/SMIG/rhodamine_reader.html

http://www.sensient-tech.com/solutions/industrial_other.htm

http://www.dyes.com/

5.4 Mitigation Schemes

Objective
To optimise layout of proposed layout of Post-Panamax forebays, salt pit arrangements and location of spill water intakes. Assess seasonally dependent flushing strategy and application of WSBs.

Methodology
Apply the established 3D hydrodynamic model of the forebay and lake. Implement the new layouts and optimise these for minimum salt intrusion. Investigate benefit of a seasonally dependent flushing strategy.

Results
Optimised layout and flushing strategy for Post-Panamax Locks. Optimisation will be based on computed salinity maps and gradients in the vicinity of the locks for Post-Panamax Locks. Interaction between new and old locks should also be assessed.

5.5 Monitoring Programme

5.5.1 Long-term Measurements of Salinity

Objective
Establish a baseline observation system for salinity. From an ecosystem point of view, salinity gradients and residence time of water bodies should be determined. Provide the basis for a functional based ecosystem analysis impact assessment. This information can be applied to soften environmental requirements.

Methodology
The change in space and time of the salinity in the Canal System is recommended to be followed through a monitoring programme including measurements along transects from the locks to the inflows to the lake as well as in tributaries (rivers and streams).

The programme is recommended to include high precision and sensitive conductivity measurements describing the dynamic in the areas through the different yearly seasons. The programme may include automatic monitoring. The sensitivity of the measurement has to be less than 0.1 ppt. Please refer also to Section 5.3 above.

These measurements are recommended to be carried out supplementary to a water sampling programme with laboratory analysis of the chloride content of the water. Samples are to be collected from transects from the locks to the inflows to the lake as well as in the inflowing water in rivers and streams.

It is most important to measure outflow salinity in the Gatun and Miraflores stilling basin. This will also provide an independent check/validation of SWINLOCKS.

Results
Long term measurements of salinity for establishment of baseline conditions and trend analysis.

5.5.2 *Hydrodynamic and Salinity Modelling for Monitoring*

Objective
Run hydrodynamic models of the Canal System that can simulate residence time and renewal of water bodies and salt transport for the period of monitoring. Provide hydrodynamic information for interpretation of measurements.

Methodology
Set up a hydrodynamic model. A 2D model must be considered adequate. Salt exchange must be parameterised, see also Section 5.2 above. Eventually this model can be made operational in real time conditions in combination with measurements for monitoring of the Canal System and a systematic data collection.

Results
Continuos maps of water mass and salinity distributions during monitoring.

5.5.3 *Evaluation of Biological Effects – Literature Review /Model Based Assessment*

Objective
Assess criteria for definition of freshwater and define a biological monitoring programme.

Methodology
A literature review is recommended performed aiming at summarising the known tolerances for freshwater organisms for salinity. Focus has to be on low salinity e.g. less than 1 ppt. and organisms relevant to the areas in question. Furthermore, effects on physical/chemical processes (flocculation, adsorption, desorption etc) are to be covered.

Results
Identification of sensitive key species for biological monitoring. Based on the literature review, the monitoring data and especially the modelled distribution of salinity through out the different yearly seasons, an assessment of expected effect can be given.

5.5.4 *Biological Monitoring*

Objective
Monitor biological state with emphasis on salt water influence.

Methodology
Based on the above-mentioned literature review, key species are to the possible extent selected for an ongoing monitoring programme. Abundance of the species is to be monitoring on location in the vicinity of the locks as well as on reference stations. The key-species-monitoring is recommended supplemented with a broader biological characterisation of benthic and pelagic species composition and abundance.

The data from the monitoring programme has to be evaluated based on information from the salinity monitoring programmes and the modelling results of the salinity distribution in the lake throughout the yearly seasons.

It is foreseen that the biological monitoring programme has to be carried out over a time period of several years to evaluate to which extent changes are due to natural fluctuations or due to salinity changes induced by the lock operation. However, a well designed monitoring programme combined with appropriate modelling can be a very powerful tool in the attempt to distinguish between salinity induced changes and changes induced by other reasons.

Other environmental factors may as well play a role for the biological variation, why other environmental and water quality variables may be relevant to monitor. Further details and evaluations are needed to decide on this.

Results
Biological baseline condition and scientific basis for assessment of possible changes due to change in salinity conditions and distribution.

Note: ACP is presently undertaking regular water sampling as part of a continuous monitoring programme for water quality. The above listed activities should be coordinated with these activities.

6 REFERENCES

Ref. /1/ Kerstma J., Kolkman P.A., Regeling H.J and Venis, W.A. Water Quality Control at Ship Locks. Prevention of Salt- and Fresh Water Exchange. 1994 A. A. Balkema Rotterdam the Netherlands.

Ref. /2 Carsten Jurgensen. Entrainment Introduced by Piers, Dams, and Ships in a Stratified Channel Flow. PhD Thesis. Technical University of Denmark, Lyngby, 1989.

APPENDIX A

Analysis of a Single Lock, Supplementary Model Results

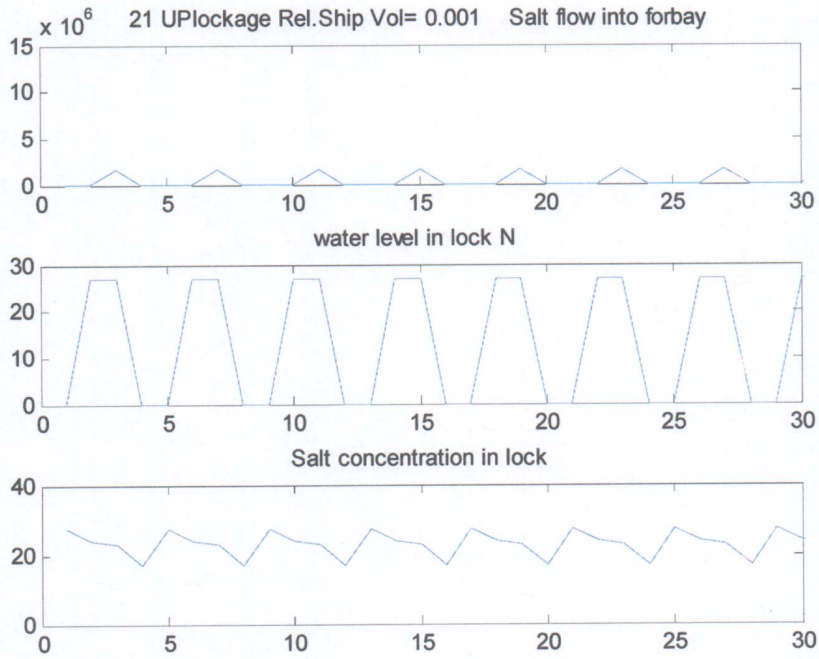

Figure A1 Uplockage. One lift lock, with 6 water saving basins, ship volume is equal to 4,000 m^3

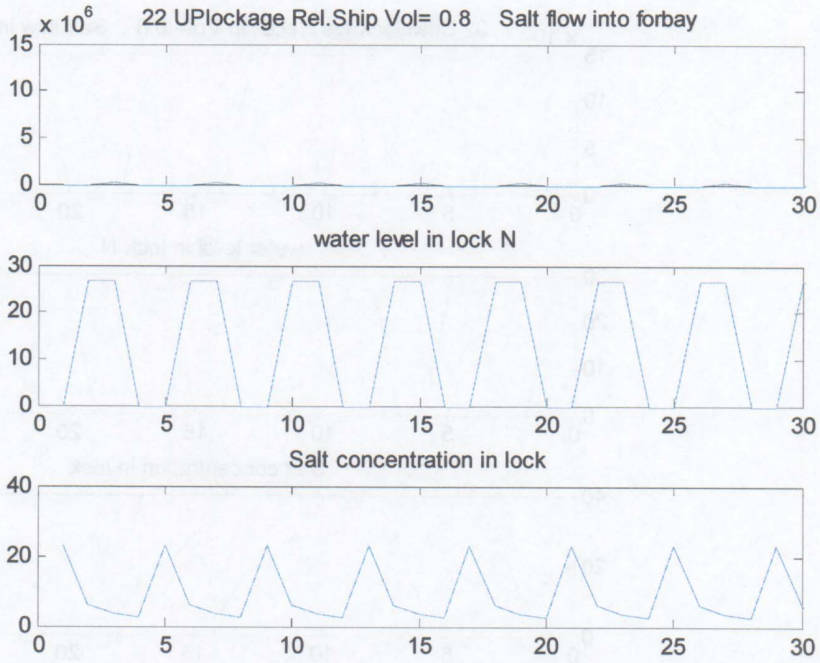

Figure A2 Uplockage. One lift lock, with 6 water saving basins, ship volume is equal to 320,000 m ^{3}

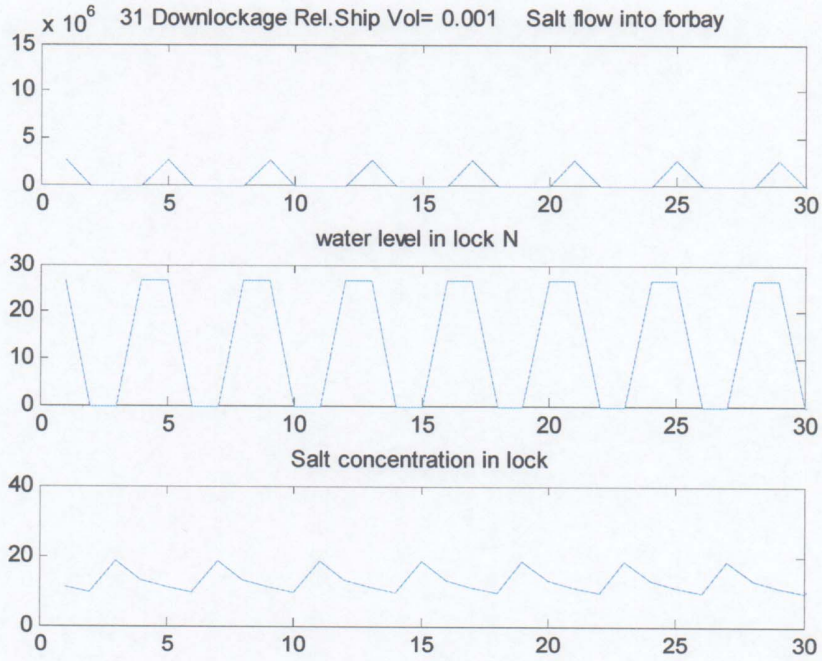

Figure A3 Downlockage. One lift lock, with 6 water saving basins, ship volume is equal to 400 m^3

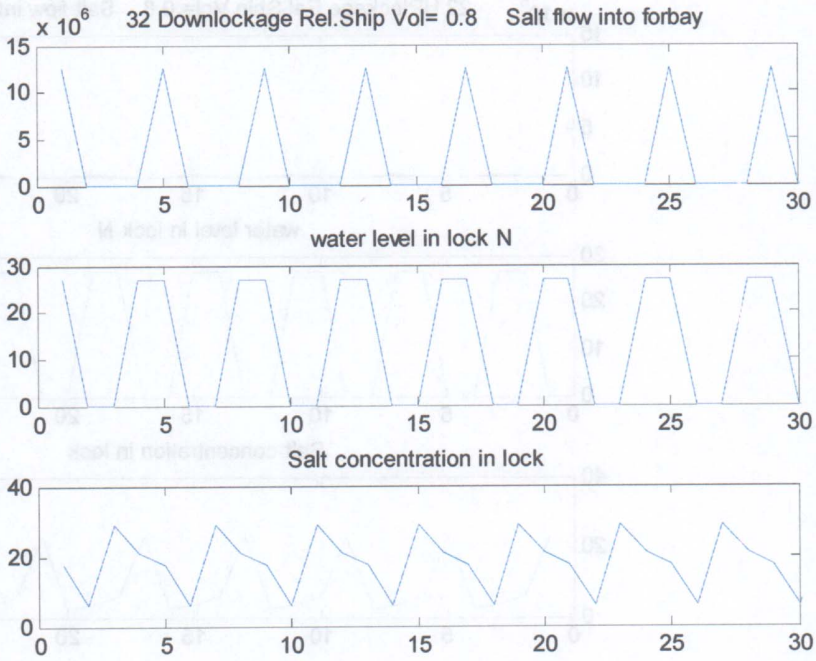

Figure A4 Downlockage. One lift lock, with 6 water saving basins, ship volume is equal to 320,000 m^3

A P P E N D I X B

Brief Description of the Panama Canal System and Hydraulic Processes

Brief Description of Canal System

The longitudinal profile of the Panama Canal is shown in Figure C.1. At the Atlantic entrance the double three-lift Gatun Locks lead to the Gatun Lake. Through Gaillard Cut the canal leads to the one lift double Pedro Miguel Locks and Miraflores Lake. From here the two lift double Miraflores Locks are connected to the Pacific entrance.

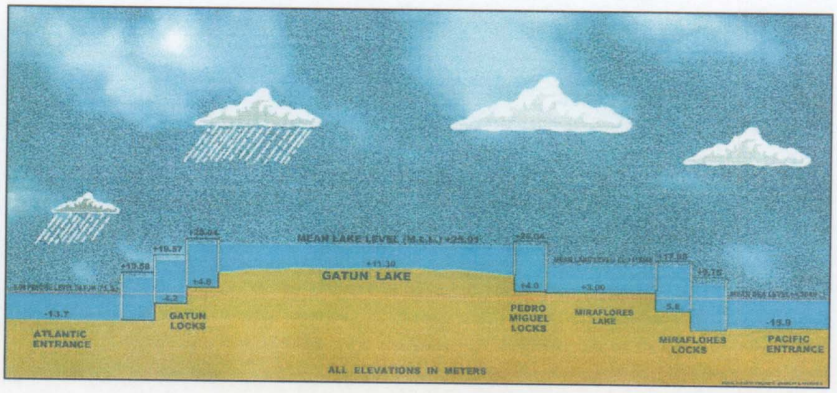

Figure C.1 The profile of the Panama Canal system (by courtesy of ACP)

The Gatun Locks lift about 26 m to the Gatun Lake that has a mean water level of +25.9 m above Precise Level Datum (PLD). The water level in the Gatun Lake varies with the season and the variation is at maximum 2.8 m. The Gatun Dam maintains and controls the water level in the lake and Gaillard Cut. The water level of the Miraflores Lake is about +16.6 PLD and is controlled by the Miraflores Spillway. Thus, the Pedro Miguel Locks lifts 9.3 m and the Miraflores Locks 16.6 m.

An overview of the locks is shown in Table C.1 below.

Table C.1 Nominal dimensions and water levels in locks and lakes, ref. Report A.

Basin	Pacific Side				
	Nominal lock dimensions (m)		Nominal, mean water level (m to PLD)		
	Length	width	high	low	Lift
Gatun Lake			+25.91		
lock C	332.1	33.5	+25.91	+16.46	9.45
Miraflores Lake			+16.46		
lock B	332.1	33.5	+16.46	+7.92	8.53
lock A	329.2	33.5	+7.92	+0.30	7.62
Pacific Ocean				+0.30	

Basin	Atlantic Side				
	Nominal lock dimensions (m)		nominal, mean water level (m to PLD)		
	Length	width	high	low	Lift
Gatun Lake			+25.91		
lock F	329.2	33.5	+25.91	+17.38	8.53
lock E	329.2	33.5	+17.38	+8.54	8.84
lock D	332.1	33.5	+8.54	+0.06	8.48
Atlantic Ocean				+0.06	

The locks operate 24 hours per day and start with uplockages in the morning followed by downlockages at noon. Later on during the night the sailing direction is again changed from downlockage to uplockage.

The lock filling is gravity driven. The lock is filled with water taken from the lake (Gatun Lake-Gaillard Cut and Miraflores Lake) that fills into the lower lock during lockage. Thus nominal lengths, width and lifts of the locks determine the quantity of spilled lockage water. Infilling takes place through the bottom and the walls of the locks.

The operation of the locks is illustrated in Figure C.2 below.

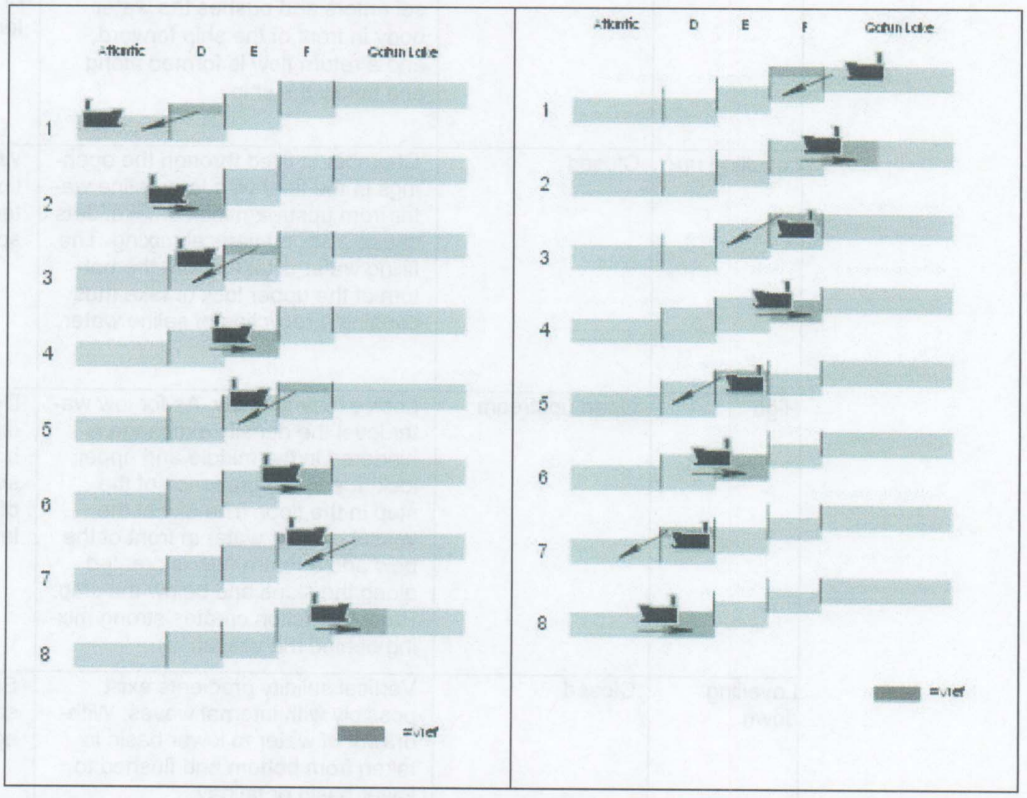

Figure C.2 Illustration of the operation of the Gatun Locks for uplockage (left) and downlockage (right) from ref. Report A. The arrows indicate the direction of salt exchange SE and Vref is a reference volume, see also section 4.3

Hydraulic Processes in Locks

In Report A the following hydraulic processes and parameters affecting the salt water intrusion have been identified, see Tables C.2 and C.3. A distinction is made between uplockage and downlockage.

Table C.2 Hydraulic processes and parameters during uplockage

Uplockage			
Water level in lock chamber	***Gates***	***Hydraulic processes***	***Important Parameters***
Low	Open downstream	Lock exchange flow. In the middle and upper locks the intruding density current is hindered by the upward step in the lock floor. The vessel enters and pushes the water body in front of the ship forward and a return flow is formed along and below the ship	Density difference, dilution of water body in tailbay, size of vessel, time of opening, propeller action of vessel
Levelling up	Closed	Chamber is filled through the openings in the floor with less saline water from upstream lock or lake. Jets cause a strong vertical mixing. The filling water is taken from the bottom of the upper lock or lake thus causing a recycling of saline water.	Water level variation in tailbay determines amount of spill water
High	Open upstream	Lock exchange flow. As for low water level the density exchange is hindered in the middle and upper lock due to the presence of the step in the floor. The exit of the vessel pushes water in front of the bow and a return flow is created along the sides and below the ship. Propeller action creates strong mixing behind the vessel.	Density difference, dilution of water body in tailbay, size of vessel, time of opening, propeller action of vessel
Levelling down	Closed	Vertical salinity gradients exist possibly with internal waves. Withdrawal of water to lower basin is taken from bottom and flushed to lower basin or tailbay.	Spill water is more saline than average water body

Table C.3 Hydraulic processes and parameters during uplockage

Downlockage			
Water level in lock chamber	***Gates***	***Hydraulic processes***	***Important Parameters***
High	Open Upstream	Lock exchange flow. In the middle and upper locks the intruding density current is hindered by the upward step in the lock floor. The vessel enters and pushes the water body in front of the ship forward and a return flow of more saline water is formed along and below the ship towards the forebay or upstream lock.	Density difference, dilution of water body in tailbay, size of vessel, time of opening, propeller action of vessel. For most upper Gatun locks and for Pedro Miguel density effects are small.
Levelling down	Closed	Chamber is filled through the openings in the floor with less saline water from upstream lock or lake. Jets cause a strong vertical mixing but this is influenced by the presence of the vessel. The filling water is taken from the bottom of the upper lock or lake thus causing a recycling of saline water. A high tide causes less spill water and thereby less flushing of saline water.	Tidal variation in tailbay
Down	Open downstream	Lock exchange flow. As for high water level the density exchange is hindered in the middle and upper lock due to the presence of the step in the floor. The exit of the vessel pushes water in front of the bow and a return flow is created along the sides and below the ship whereby more saline water is drawn into the chamber. Propeller action creates strong mixing behind the vessel.	Density difference, dilution of water body in forebay, size of vessel, time of opening, propeller action of vessel
Levelling up	Closed	Vertical salinity gradients exist possibly with internal waves. The chamber is filled up with water from the upper lock or forebay. This is less saline and due to the jets an almost homogenous water body exists at the end of the filling process.	

According to Report A there are several differences between uplockage and downlockage. During uplockage the upward movement of the ship volume moves an equivalent less saline water body downwards. Salt intrusion during uplockage is therefore primarily due to lock exchange flow. During downlockage the situation is contrary. The movement of the ship volume forces a more saline water body upwards. This causes a salt intrusion that is working together with the salt intrusion due to density differences (lock exchange).

Comments: *Salt intrusion is most pronounced during downlockage and much less during uplockage. Movement of ship volume is more important than classical density lock exchange effects. The analysis of hydraulic processes is based on measurements, complete, well documented and scientifically sound.*