# Salt Water Intrusion Analysis for Post Panamax Locks – Report A

# Análisis de la intromisión de Agua Salada en Esclusas Pospanamax – Informe A


## WL Delft Hydraulics



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**Resumen**

Prepared for:

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# 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

Tom H.G. Jongeling

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WL | delft hydraulics

# 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:

- 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

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).