Tropical Lake Ecology Assessment
With Emphasis on Changes in
Salinity of Lakes
Project No.SAA-140714
Final Technical Memorandum # 6
Model Evaluation

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Prepared by:
URS Holdings, Inc.

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1.0 INTRODUCTION

The Panama Canal Authority (ACP) is currently performing a series of studies to assess the feasibility of a new set of locks, alternative systems to raise and lower vessels, and upgrading the navigation channel to prepare a Master Plan for the Modernization and Expansion of the Canal. Parts of these studies include the analysis of risks to increase the salinity of the lakes Gatun and Miraflores. This may occur as a consequence of increased traffic, lateral water saving basins, and anticipated structural modifications, which include an additional set of locks to accommodate larger Post-Panamax vessels. Lake Gatun is adjacent to the locks on the Atlantic and Pacific sides of the Canal and Miraflores Lake is adjacent to the locks on the Pacific side of the Canal.

Within this context, ACP retained URS Holdings, Inc. (URS) for the execution of the contract for the Tropical Lake Ecology Assessment with Emphasis on Changes in Salinity of Lakes. More specifically, under this agreement, URS shall recommend the maximum salinity levels, which may be tolerated in the lakes mentioned above. The salinity standards must consider the current procedures for treatment of potable water in Panama and must also maintain the biological integrity of freshwater ecosystems.

The terms of reference specify several intermediate products in the form of technical memoranda. In this context this is the sixth technical memorandum, which deals with the consultation with the salinity modeling contractor and the evaluation of salinity model simulation results.

1.1 OBJECTIVE

Based on the previous paragraphs, the objective of this sixth technical memorandum is to present the results of the evaluation of the documents reviewed that deal with salinity model developed to simulate existing lock operations and future post-panamax locks operations.

1.2 BACKGROUND

A series of seven reports have been issued by WL | Delft Hydraulics (Delft) as a result of contracts with the ACP. Five of this series of reports, designated A through E, were completed between June 2003 and April 2004. The two others are not identified as part of the sequence distinguished by letters. These two are studies of the salinity intrusion in a version of the three-lift Post Panamax locks (September 2004) and an evaluation of salt water intrusion mitigation systems for these same envisioned locks (October 2004). URS has conducted a review of these reports to verify the modeling analyses that were conducted. These analyses were largely based on a specially configured numerical model of the present conditions. It was subsequently used to predict the amount of salinity intrusion above the locks for several different design options for new, larger locks. The model was originally designated simply as the Simulation Model. In the later report this designation changed to the name SWINLOCKS. This latter appears to be the same basic model with the additions of a number of special features to represent various water saving basins and salt water intrusion mitigation systems.

The designation of the reports is somewhat confusing. There are three separate volumes that we will distinguish as the June 2003 Volume, the September 2003 Volume, the April 2004 Volume and the two additional reports (September 2004 and October 2004). The June 2003

Volume contains only Report A. The September 2003 Volume contains somewhat lengthy discussion of the analyses of the Post Panamax situation using a numerical model followed by separate sections labeled Report B, Report C and Report D. The third volume (April 2004) contains only Report E, which in itself has two parts. Part I discusses the effect of water recycling at the Pacific side of the canal and Part II covers alternative methods to mitigate salt-water intrusion. Report F includes two documents that first appeared as separate volumes in September 2004 and October 2004. These cover additional salt water intrusion simulations of the Post-Panamax locks, with dimensions updated from the previous simulations and model simulations concerned with various possible special salt water intrusion mitigation systems that could be applied to the Post-Panamax locks.

We have organized this review to follow this same sequence. Our major divisions distinguish the individual volumes.

Our review is specific to the modeling aspects of the work. We have focused on the adequacy of the numerical model and required input data. We also comment on the strengths and weaknesses of the specific ways that the models were applied to the evaluations of the relative effectiveness of the different options that have been considered. These comments include thoughts regarding the applications and limits to predictions of salt water intrusion under a variety of possible future scenarios.

Report A, in the June 2003 volume, covers the existing situation. It includes a discussion of the overall approach that used a combination of field measurements and numerical modeling. The model is generally described. The field measurements are also described and the results are given in the forms that are needed to both confirm the assumptions used in developing the numerical model and to verify the correct operation of the model.

The other reports in this series analyze a series of design concepts for the planned, larger, Post-Panamax Locks and associated options designed to mitigate salt-water intrusion and freshwater use in the new system. Reports B, C, and D cover single-lift, three-lift and two-lift locks respectively. Report E explores the effect of water recycling at the Pacific side canal and alternative methods for minimizing salt-water intrusion. The two additional reports further refine these analyses.

The organization of this review report is focused on the applicability and validity of the Simulation Model and an assessment is used to predict conditions during the operation of the envisioned post-panamax locks. Portions of Report A that are not specific to the evaluation of the model are not detailed in this review. Similarly, an emphasis is placed on Report C in preference to Reports B and D because the three-lift design is clearly favored. The reports dealing with possible future systems to conserve freshwater and to mitigate salt water intrusion use the same model so our emphasis is shifted to evaluations of the model cases and the interpretation of the results.

1.3 STRUCTURE

This Technical Memorandum has been organized in a manner that is consistent with the objectives of the document and that will allow a clear and concise evaluation of the saltwater intrusion simulation work performed to date. The structure of the document is briefly discussed in the next paragraphs.

Introduction. This introductory section contains a general description of the work to be carried out by URS as well as the objective, and structure for the Technical Memorandum. In addition, background information that explains the various documents reviewed as well as the priorities established for evaluation is also presented.

Evaluation. This section is the primary result of Task 6 of the project and presents a brief summary of the documents reviewed followed by an evaluation of the strengths and weaknesses of the results obtained by the simulations.

Bibliography. Lists of relevant documents consulted during the preparation of the document are presented in this section.

2.0 EVALUATION

This evaluation sections has been organized into three distinct sub-sections that include: document summary; review of saltwater intrusion modeling; and review of model applications and predictions.

2.1 DOCUMENT SUMMARY

In order to make meaningful comments on the reports it is necessary to establish a certain amount of background. To this purpose, we first summarize the major parts of the individual Delft reports. This is followed by our review comments.

2.1.1 The June 2003 Report (Report A – Existing Conditions)

Overall, the goals of the Delft work were to: a) understand the present situation and, b) to predict the effectiveness of various design options for limiting the amount of salt water passing through the envisioned post-panamax locks. The main tool is the numerical model. Therefore, it is sensible to begin our review comments with a brief summary on this model. Most of the project effort was devoted to applying this model to the specific conditions of the canal locks, to developing the data necessary to support this model and in interpreting the model results.

The Simulation Model

The numerical model used in the Delft analyses was simply named the "Simulation Model" but this became SimLocks later in the sequence of reports. The model represents the movement of ships and water masses through the canal locks in a quantitative framework. Rather than to attempt to represent all of the fine details of water flow between chambers and around the ships as they transit the locks, this model uses a volume-averaged approach. Each lock chamber or basin is a node in the model that has a unique volume and salinity assigned to it at each time-step of the model. The transit of individual ships is represented as a series of individual steps that bring about exchanges of volumes and their associated salinities between the nodes.

In this model a number of separate basins represent the lock chambers and the lakes. In addition, artificial basins have been created in the model to represent the section of the lakes and estuaries immediately adjacent to the upper and lower locks. These are called the "forebays" and "tailbays". They represent the portions the lakes and estuaries that are so close to the locks that water discharged into them during locking operations can flow back into the adjacent lock chamber in a subsequence step of lock operation. Without these artificial basins (that exist only in the numerical model) all of the water discharged from the locks would be assumed to quickly mix over the whole volume of the lake. In fact, although this point is not well stated in the reports, it appears that water exchanged from these artificial basins with the adjacent lake or estuary is assumed to mix over the whole volume of these larger water bodies.

Each basin has a water volume associated with it that can change according to simulated lock operations or as a result of model inputs. Basins are nodes that can exchange water volumes and salt concentrations through links with adjacent basins. These links are arranged to represent the actual physical connections that characterize the actual canal, exchanges

between the forebays and tailbays and either the adjacent lock or larger water body, and, in the later reports, exchanges with water saving basins. Both fresh and saltwater volumes are exchanged between the modeled lock chambers as a result of filling and emptying during the movement of a ship between chambers and as the result of denser salt-water underflow as the lock gates are opened.

The model represents the passing of time as a sequence of time-steps of fixed (short) duration. Each step in the sequence of steps associated with ship movements through the lock systems has an associated duration. At the conclusion of each step the water volumes and salt concentrations adjust and nodal status parameters are reset. The general nodal status parameters are: water level, water depth, water volume, and salt concentration. In the Atlantic and Pacific tailbays the status parameters are the water level and salt concentration. The status parameters for the model basins representing Miraflores and Gatun Lakes are: water level, lake water volume, and a volume-averaged lake salt concentration. Other parameters are associated with the model basins to represent their physical dimensions, time-varying water level and volume, volume-averaged salinities, auxiliary discharges, detailed features and a running count of the time.

The Simulation Model does not attempt to represent the actual details of the water flows during the volumes exchanges. Instead, these processes are summarized as volume-averaged exchanges. The volume-averaged salt fluxes between the model's basins are computed using exchange coefficients. The exchange coefficients are empirically set during model calibration so that the behavior of the model best matches actual measured values.

Two factors complicate this modeling representation of water exchanges between the chambers and basins. The density of the water depends on its salinity and temperature. In this case salinity effects dominate. Saltier water is denser than freshwater. Although this density difference is small, with a theoretical maximum of only about three percent, it is usually enough to cause the saltier water to underflow the fresher water when the lock doors open. This density difference is also enough to inhibit mixing due to the natural turbulence of these exchange flows. Thus, there is a tendency for there to be a vertical gradient of salinity in the lock chambers. Although these gradients could be fully erased by mixing due to moving the ship ahead using its propellers, this is not always complete. The degree to which this mixing is incomplete depends on a number of factors including the relative displacement of the ship compared to the volume of the lock chamber, the magnitude of the original salinity gradients, and the source and flow rates of the lock chamber inflows and discharges. Also, some steps in the lock operations, such as turn-arounds between sequences of up-locking and down-locking, vessels do not involve ship movements so that the flow and mixing of the water volumes are controlled by other processes.

The individual steps in the process of locking a ship through the series of individual chambers are associated with different water flow patterns and mixing processes. For example, the process of up-locking a ship from a lower lock to an upper one has two distinct stages of water flow. Water is exchanged and mixed as the lower chamber is filled and the water levels are equalized. Then a different form of water exchange is caused by the translation of the ship between the lock chambers. As the ship moves into the upper lock a water volume equal to its displacement must move back towards the lock chamber that it left.

Another example is provided by the way that the artificial forebay and tailbay sections are used in the model. Their purpose is to allow the model to represent conditions where some

water emptied from a lock is drawn back into that same lock during a subsequent step in the processes. This is complicated by the fact that this water is always free to leave these artificial basins on the sides away from the locks. This means that the volume-averaged salinity of the water in the tailbays and forebays changes in time. To represent this time-dependant behavior in the numerical model it is necessary to use exchange coefficients that also vary in time, depending on the duration of a particular lock operation that is being simulated.

Because the model uses a volume-averaged approach to avoid the nearly hopeless task of representing the fine details of water flow and mixing in each of the steps representing real lock operations, it is necessary to determine exchange coefficients for each of these different steps. The exchange coefficient for a particular step is intended to quantify the overall volume-averaged result in the salinity concentration during water volume transfers between model nodes. Although this would be a straightforward approach if there were always complete mixing it becomes quite complicated when representing real conditions where there are persistent vertical salinity gradients. Given these complications it was necessary to carry out field programs during the wet and dry seasons to measure the changes in salinity during different steps in the transits of various size vessels. The resulting data, which exhibited a significant amount of unexplained variability (ie. scatter) were then fitted with exchange coefficients for use in the numerical models.

In addition to model inputs describing the physical dimensions and flow exchange processes of the locks there were other inputs for tide levels, seasonal initial salinity conditions, water levels in the lakes, and auxiliary water releases for hydroelectric power generation and system overflows. The freshwater input to Gatun Lake is a model input that sets the water level of this basin. It is varied to represent the wet and dry seasons according to patterns obtained from long-term lake level records. Water levels change as a result of flows out of the canal through the locks and through spillways on the Pacific end when there is surplus of fresh water. The withdrawal of freshwater by the power station and as cooling water is also represented in the model.

The basic Simulation Model represents the two lanes of locks on both the Atlantic and Pacific ends of the canal according to the system schematic diagram shown on Figure 2-1 (notice that withdrawal of potable water is considered as negligible). Ship movements in either direction are simulated by a series of ship movement steps described by the displacement of the vessel, the duration of its movements, the lane of locks that it transits, and the relative pattern of up- and down-lockages. Because the beam and the displacement volume of the ships strongly impact the water exchanges between the lock chambers and other basins, a system has been arranged to simulate the passage of four classes of ships. These values, as provided by ACP, are shown in Table 2-1. The “zero” class is used to simulate the occasions when the locks are operated without a ship.

Table 2-1
Types of Vessel in Simulation Model

vessel class	water displacement S	Beam	length	draught	percentage of number of transits
0	0	-	-	-	-
I	15,000 m^3	21.3 m (70 ft)	150 m (≈ 500 ft)	4.7 m (15.4 ft)	45
II	45,000 m^3	27.4 m (90 ft)	215 m (≈ 700 ft)	7.6 m (24.9 ft)	20
III	90,000 m^3	32.0 m (105 ft)	275 m (≈ 900 ft)	10.2 m (33.5 ft)	35

Source: ACP

The type of ship, its direction of movement through the canal, and the sequence of lock operations associated with its transit make up a model scenario. Other special scenarios are used to simulate the occasional water releases at the Gatun and Miraflores Dams or the sequence of lock operations that characterize a 'turn-around' period. The 'turn-around' sequence occurs as the water levels in the lock chambers are changed from the pattern used to uplock a series of vessels to the configuration of water levels needed to downlock a subsequent series of vessels (or vice versa). Because the actual operation of the canal favors a 'semi-convoy' mode wherein a groups of ships pass in the same direction, the models uses 'day-patterns' to describe the traffic flow. That is, several sequences representing patterns of ship transit scenarios were created and tabulated as a 'day pattern'.

The day pattern used to validate the model serves as an illustration. This consists of 36 transits a day (18 in each direction). As each transit has an up-lockage and a down-lockage phase, there are 72 ship movement scenarios and an average of 8 turn-around scenarios in this day case (Report A, Page 6-2). This case also includes three water release scenarios representing a combination of spillway, hydropower and cooling water discharges. The case also contains a fixed number of the different ship sizes (according to the class sizes given in Table 2-1). This day pattern was selected to 'generally' represent the typical flow of shipping through the canal on a 'typical' day scenario as provided by ACP.

During the model validation this fixed day pattern was repeated for each day of the simulation. In general, a sequence of day patterns was combined with an environment description (water levels, water volumes, and salt concentrations) to make 'cases'. A number of different fixed cases were developed.

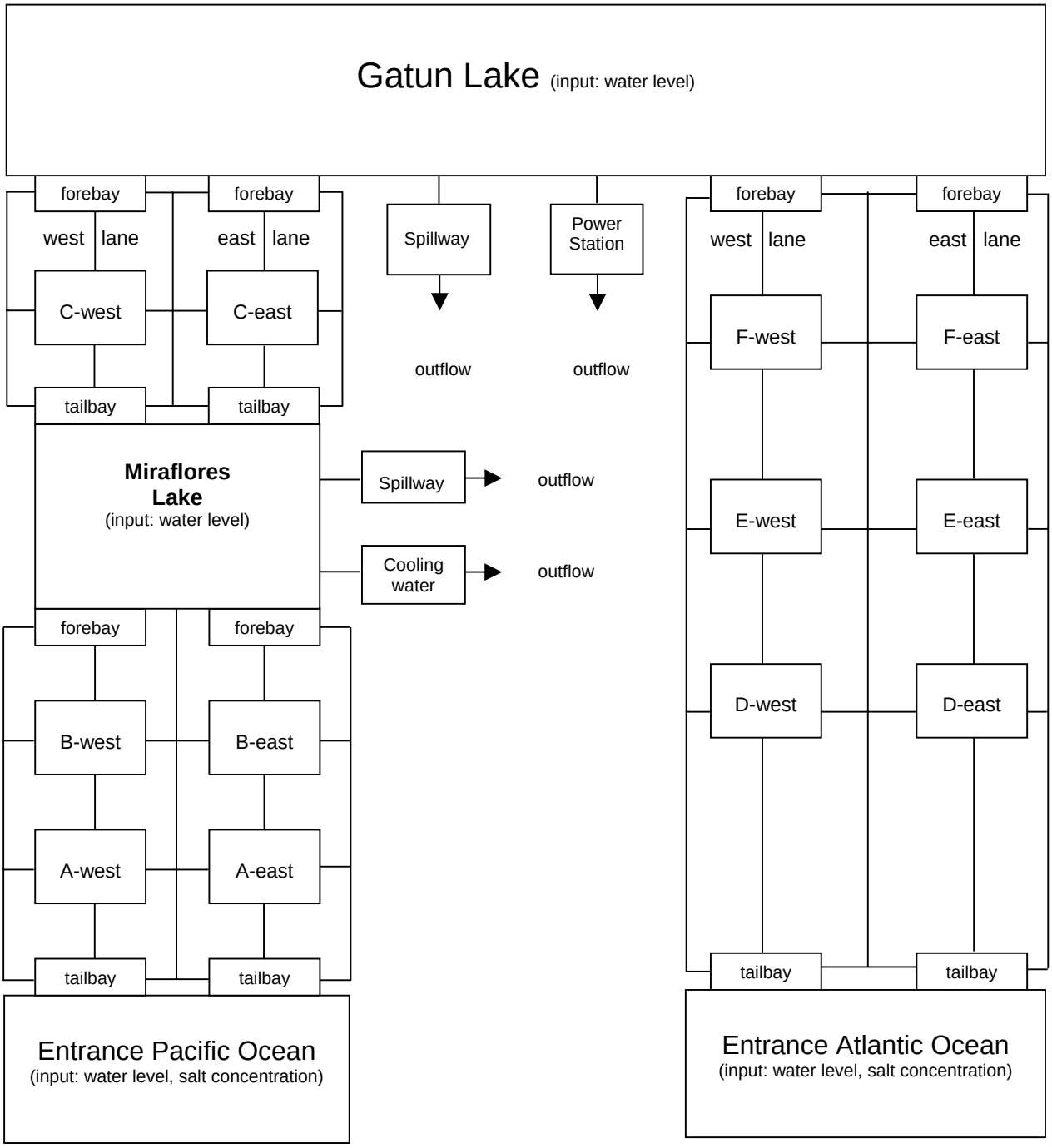


Figure 2-1. Simulation Model Nodes and Hydraulic Connections (Redrawn from WL | Delft Hydraulics)

For each step in the ship movement scenarios within a given case there is a corresponding set of one (or more) empirical exchange coefficient(s). According to the procedures used in this modeling, different cases can be created from the same sequence of day patterns and environmental descriptions by using alternative values for the exchange coefficients. Rearranging the day patterns, the sequence of day patterns, the environmental descriptors, and the individual exchange coefficients can develop other cases.

The model testing was conducted with a number of simple test cases, some without any ship movements. These simple cases allowed individual modeling steps to be checked and corrected, if necessary. Presumably, the model spin-up conditions were established during this part of the work. Model spin-up refers to the model interval required for the initially set parameters (eg. salinities) to slowly adjust and come into a steady state balance with the controlling conditions. These could be far from balanced initially and the resulting output values would not represent the real case until the model spin-up duration has been exceeded. It was found that stable salinity regimes required the model-equivalent of two years to develop.

After the testing was complete the model was validated against actual data taken during the wet and dry seasons. A single standard pattern of ship movement scenarios was used. A number of different cases were tried by changing the durations and exchange coefficients associated with the ship movements. The exchange coefficients for water releases at the Miraflores and Gatun Spillways were also varied to obtain realistic results. This was especially important for the Gatun Dam because the model demonstrated a strong sensitivity of the computed salinities at both dams and within the Gatun Lake to this parameter.

The report concludes that with the appropriate adjustments to the model cases realistic volume-averaged salinities were computed for Miraflores and Gatun Lakes under both wet season and dry season conditions.

2.1.2 The September 2003 Volume

This report contains a section entitled "Comparison of salt water intrusion for the three-lift, two-lift and single-lift configurations of the Post-Panamax Locks". This is a clarification of some of the contents of Report A and a discussion of the procedures used to apply the Simulation Model to the Post-Panamax situations. Here it is established that some limited modeling has been carried out using the Delft3D model to represent some of the detailed flows and salt concentrations during simulated transits of a ship between locks. As expected, the 3D model was very cumbersome to use in terms of the amount of effort needed to set it up and the computational time of individual model runs. Additional auxiliary modeling was done with the Delft 2DV numerical model. This is a detailed hydrodynamic model with a grid representing a vertical section along the central axis of the locks. It is useful because it is simpler to apply than the 3D model but, although it portrays the flow under a ship as it enters a lock, it cannot represent the flow around the sides of the ship. So both the 3D and the 2DV models have limitations and field measurements are considered the most accurate source of this information. For these reasons, the detailed hydrodynamic models were used only for restricted cases to help in evaluating the exchange coefficients used in the Simulation Model.

The most important statement in this first section of the Sept. 2003 Volume is the statement given on page 5-1. "The exchange coefficients that will be used in the simulation model for the future situation are selected on the experiences with the existing situation and on Delft3D density-flow computations for the single-lift lock."

Report B – Future situation: Post Panamax Locks [Single lift Locks]

This report covers the single lift configuration. It clearly concludes that this configuration produces considerably more saltwater intrusion into the canal. When water saving basins are included in the analyses the situation is worse. Some analyses were conducted to establish the

sensitivity of these results to the selection of the exchange coefficient for the single-lift lock case. It was found that there were considerable variations in the predicted salinities in Miraflores and Gatun Lake because of this effect but, overall, there was no doubt that the single lift configuration created the most salt intrusion of the different cases considered.

These findings make this case the least interesting and no additional review is warranted.

Report C – Future situation: Post Panamax Locks [Three lift Locks]

The salt-water intrusion for the three-lift Post-Panamax lock situation is covered in this report. The Simulation Model was modified to portray the additional lanes of three locks each on both the Atlantic and Pacific ends of the canal. Figure 2-2 shows a schematic of the model representation. Each new lock is a separate basin in the model. These are larger than the existing basins in correspondence with the envisioned larger dimensions of the large locks. There are basins in this version of the Simulation Model that represent the forebay and tailbay of the new lock sets just as there were for the existing situation. The three 'new' locks on the Pacific side are to have an approach channel that routes around Miraflores Lake. There is a direct connection, through a forebay basin, between the new upper Pacific lock and Gatun Lake.

The Simulation Model is set up with the option to include water saving basins in the simulations of lock operations. These are simply basins connected to each of the new locks where water can be temporarily stored during the emptying of the lock for use in a subsequent filling.

Although the geometry and operation of the new lock systems are easily defined and included in the Simulation Model, the situation regarding the proper exchange coefficients is less obvious. Both the locks and the ships that use them will be larger than the existing locks. Delft addressed this problem by applying the Delft3D time-varying hydrodynamic model (in the 2DV configuration) to a limited number of cases that represented the transit of a ship between two locks. In general, it was found that volume-averaged exchange coefficients that produced salinity concentration results with the Simulation Model that were similar to the Delft3D runs were those also similar to coefficients derived from their field measurements during similar ship movements. Therefore, the volume-averaged exchange coefficients that were used for the Post-Panamax locks were those taken from existing situation cases. Some minor adjustments were made.

In addition to volume-averaged exchange coefficients characterizing the salt fluxes during the locking operations there are similar coefficients related to the release of water at the Gatun Dam and Miraflores spillways. It was assumed that these would be unaffected by the opening of the new third shipping lane.

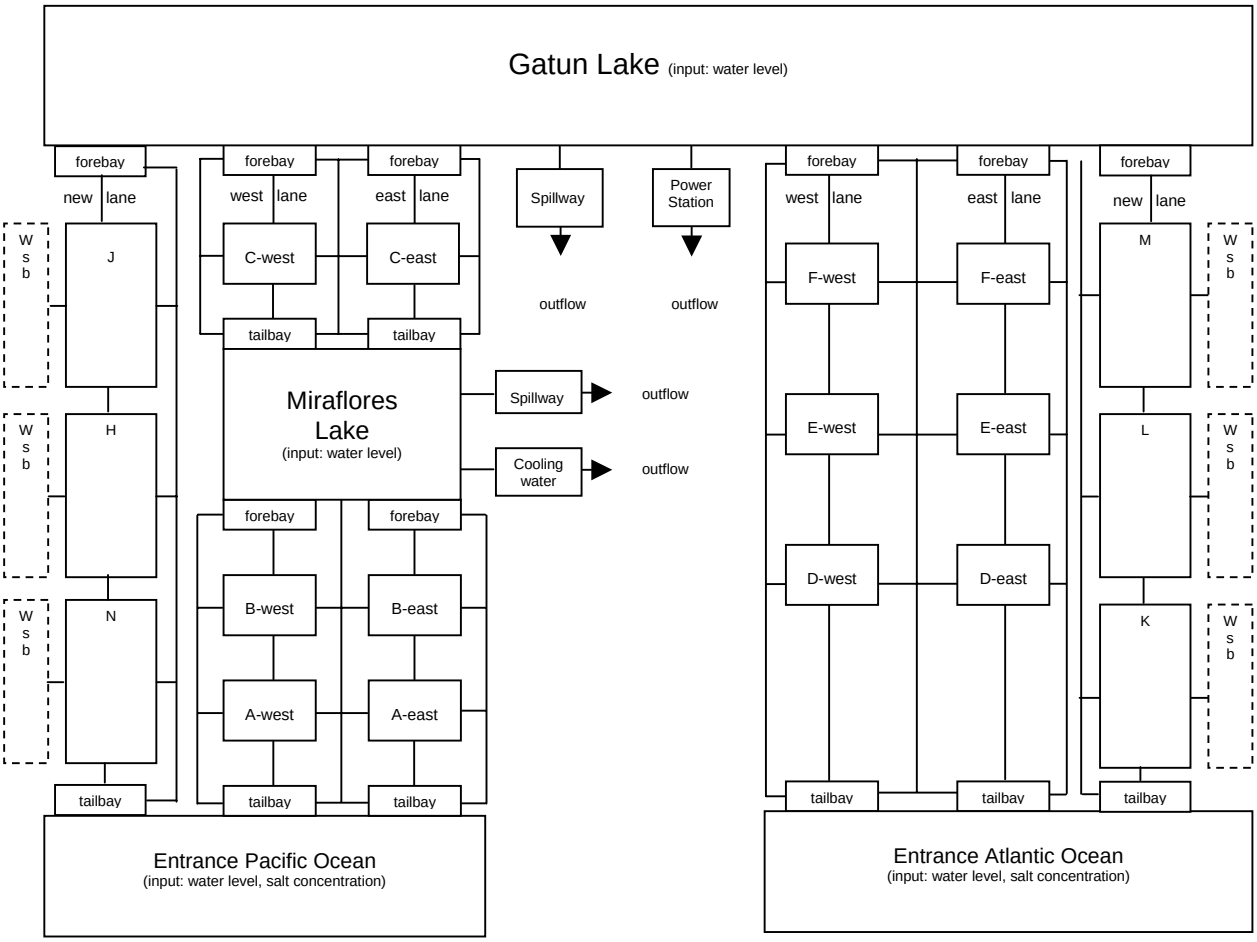


Figure 2-2. Schematic of the SimLock model as set-up for three-lift Post-Panamax lane configuration

As noted earlier in the description of the application of the Simulation Model to the existing situation, it is important to characterize the typical sequence of operations of the locks for each simulation period. For the Post-Panamax operations this required the addition of three more classes of ships to those of the existing conditions simulations that are shown in Table 2-1. These new classes are the Panamax-Plus Vessels (Type IV), the Type VII Post-Panamax with 14 m draft and the Type VIII Post-Panamax with a draft of 15.2 m. The Type VII was assumed to be in use during the first five years after the new lanes are opened.

The modeling was done to support a planning horizon extending to 2025. The ACP expected that there will be up to 5 Post-Panamax lockages per day by the year 2015, up to 10 lockages per day by the year 2025, and possibly 15 lockages per day by the year 2035. The way that the corresponding day patterns and cases were developed is not described. The day patterns for cases covering the various lockages per day are tabulated. Model simulations were conducted for wet and dry seasons and both with and without the water saving basins.

The results are shown for the expected lockages per day over the planning horizon. The salt concentration levels tended to stabilize after a simulated two years of operations. In all cases there were very small changes in the volume averaged salt concentration in Miraflores Lake. However, the volume-averaged salt concentration in Gatun Lake goes up by a factor of 3.2 for 15 lockages per day in the most unfavorable case. The most favorable case with respect to

salt-water intrusion is one without the use of the water saving basins. However, the water saving basins are shown to be effective in conserving freshwater (eg. Case B1 with water saving basin indicates a 60% less water usage is required).

Report D – Future situation: Post Panamax Locks [Two lift Locks]

The option for two-lift Post-Panamax locks was analyzed. The Simulation Model was modified to have a third lane with two locks at the Pacific and two locks at the Atlantic ends of the canal. The procedures for adding these lanes, developing day patterns and cases, and simulating wet and dry season conditions were identical to the previous modeling. The same volume-averaged exchange coefficients were used for both the existing and large Post-Panamax locks. It was also assumed that the discharges at the Gatun Dam and Miraflores spillways remained the same as in the existing situation cases.

The most unfavorable case resulted in showing that, although Miraflores Lake is bypassed by the third lane, the volume-averaged salinity will double when traffic reaches 15 lockages per day after the addition of the third lane. The predicted volume-averaged salinity of Gatun Lake rises from its present very low value to values that are above the freshwater limit (ie. to a level of 0.45 ppt). Again, a case without water saving basins is the most favorable with respect to salt-water intrusion. But water saving basins are capable of reducing the usage of water per lockage by 50 %.

A sensitivity analyses was conducted to determine the effect of variations of two of the most important volume-averaged exchange coefficients on the predicted salinities in Miraflores and Gatun Lakes when 15 lockages are reached after the opening of the third lane with the two-lift arrangement. The section describing the sensitivity analysis in Report D is brief and the explanation is incomplete (see Section 7.4, Report D, page 7-5 and Figure 7.3 & 7.4). It appears to be the only sensitivity analysis that was done and described in the whole series of reports.

Although there are many parameters including several volume-averaged exchange coefficients which are scarcely supported by data and whose evaluations have considerable uncertainty, only two parameters were varied. These were the exchange coefficients representing step II (ship transits between lock chambers) during the uplock and downlocking processes. The second coefficient that was varied was the volume-averaged exchange coefficient for step I (equalization of water levels) during uplockages and downlockages. The report does not state the amount that these coefficients were varied in the sensitivity model runs. The results shown on Delft Report D Figure 7.3 indicate differences in the predicted salinities of Miraflores Lake that are an approximate factor of 2 to 3 between the minimum and maximum salt concentrations. The corresponding range for Lake Gatun is a factor on the order of 1 1/2 to 2. Although these differences in model results are unlikely to change the relative ranking of the single-, two- and three-lift options, they do show that there should be careful use of the Simulation Model results as there is considerable uncertainty about the values of these exchange coefficients.

2.1.3 The April 2004 Volume

Report E – Future situation: Post Panamax Locks [Parts I and II]

The first part of Report E covers the use of the SWINLOCKS model to explore the effectiveness of a series of water recycling systems with respect to both the amount of water conserved and the corresponding amount of salt water intrusion. The SWINLOCKS model is the same volume-averaged model previously named the Simulation Model but it has been modified to include various water recycling schemes. For the three-lift Post-Panamax lock configuration the water recycling schemes that were considered are:

Option 1 – Water is directly recycled from the tailbay to the forebay without making use of storage pond.

Option 2 – The lower lock spills to a storage pond that is continuously pumped to the forebay.

Option 3 – One storage pond provides water to the upper lock. A second accepts water spilled from the lower lock. The water is pumped from the lower to the upper ponds.

As in the previous applications, the model requires the use of exchange coefficients that account for the transfer of the salt water portions of the basin volumes. Because the actual conditions involve time-varying flow patterns with changing vertical salinity stratification, these exchange coefficients have been derived from measured data for the simulations of the existing conditions.

For this SWINLOCKS simulation of the Post-Panamax three-lift configuration these exchange coefficients were obtained from information derived from a limited number of simulations using the three-dimensional hydrodynamic model (Delft3D) and extrapolations based on data collected from the existing situation. The derivation of the exchange coefficients for the simulated water transfers between the lock chambers and the storage ponds is not well described in the report. It appears that these water withdrawals from the lock chambers would be from the lower part of the water column where the salinities are highest. In some way exchange coefficients to cover this salt water flux to the storage ponds were estimated.

This analysis also depends on the choice of ship traffic scenarios for which the model was applied. The day case that was used in most of these model simulations consisted of 15 Post-Panamax vessels per day. This case was apparently provided by ACP.

The representation of the environmental conditions is also important in this analysis. Different Gatun Lake water level control conditions were assumed. In the baseline scenario all freshwater losses due to the operation of the Post-Panamax locks are assumed to be compensated for by new freshwater sources and the new three-lift system is equipped with water saving basins. Scenario 2 is the base case without the water saving basins. Scenario 3 (with water saving basins) and Scenario 4 (without these basins) assume that the extra freshwater losses due to the new locks are compensated for by reduced releases at the Gatun Dam supplemented, when necessary, by water from new freshwater sources. Six other scenarios were also used based on different combinations of water recycling, the use of water saving basins, and access to new freshwater sources.

For most simulations the average monthly water levels over the period 1992 – 2001 were used. However, to get insight into the effects of the extreme hydrological conditions, some additional model runs were carried out with the actual seasonal variations (monthly-averaged) over the full 10-year time interval.

The results show that, as expected, direct recycling between the tailbay and forebay (Option 1) is the worst with respect to salt water intrusion. All of the water recycling options bring about significant increases in the salt concentrations of Gatun and Miraflores lakes. It was also demonstrated that predicted salt concentrations were much higher, by a factor of two, in Gatun Lake during simulations of a dry years such as 1997. Similarly, for simulations during a wet year such as 1999, the release of excess freshwater leads to substantial reductions in the predicted Gatun Lake salt concentrations compared to the 10-year average conditions.

The second part of Report E describes a series of possible methods to mitigate salt water intrusion in the Post-Panamax Locks. It is a review of methods used around the world and does not include any modeling analyses. Therefore, a summary of this report is not relevant to the URS review for Task 6.

2.1.4 Report F

This report has two sub-parts. The first discusses additional model simulations using SWINLOCKS based on revised (slightly smaller than used in earlier simulations) Post-Panamax three-lift lock dimensions. In this report the effect of water saving basins is compared with cases without these basins. The results showed that the smaller lock chamber volumes lead to significant reductions in the salt water intrusion into Lake Gatun for scenarios simulated. Without water saving basins these reductions are on the order of 25% in simulations without the water saving basins. When water saving basins are included in the simulations the predicted salt water intrusion increases significantly. Scenarios for alternative freshwater supply, water discharge over Gatun Dam and water losses through the Post-Panamax locks that are described above for Report E were again used. ACP designated minimum water levels for these simulations of 25m (82.0 feet) in Phase I and 26.2m (86.0 feet) in Phase II. ACP personnel indicated during review sessions that it was decided to deepen the navigational channel to 10.3m (34’), and therefore the 26.2 m level indicated for Phase II was not valid anymore. The day case for ship transit scenarios included ten classes of ships. Of these, five Post-Panamax classes had been used in previous simulations and two additional classes not previously used were added. Overall, this provided two classes with beams of 45.7m (150 feet).

The second part of this report is a more complete analysis of the salt water intrusion mitigation systems that were introduced in the second section of Report E. There are no SWINLOCKS model simulations and therefore this report is considered to be outside of the scope of Task 6.

2.2 REVIEW OF SALTWATER INTRUSION MODELING

Now that the important features of the Delft modeling analyses have been summarized and discussed we turn to an appraisal of the effort. The first and obvious question is whether the overall modeling approach is appropriate? Here, the answer is clearly yes. The Delft reports point out the difficulties in providing an analysis based on detailed three-dimensional hydrodynamic model. In theory such an approach is within the state-of-the-art today but it

would be enormously cumbersome to set-up and apply. Each different scenario would require a special set-up. The model run-times would be very long. A much more detailed data set than is presently available would be needed to calibrate such a model.

Clearly a more generalized model, such as the volume-averaging Simulation Model, is the most effective approach for addressing most of the questions and issues that need to be answered with respect to the present function of the locks and for predicting the effects of the envisioned Post-Panamax locks. In fact, Delft demonstrated many of the difficulties of a three-dimensional hydrodynamic model by carrying out a limited set of auxiliary analyses to help evaluate the exchange coefficients for the Simulation Model. In this effort they needed to reduce the three-dimensions to two (ie. the 2DV) to keep the effort from becoming excessive.

The volume-averaged Simulation Model allows for quantitative representation of the important aspects of lock operations during ship transits. It is not a precise tool and its accuracy depends on a number of factors that are discussed below. However, as is clearly stated in the Delft reports, this model is not a good choice for analyzing the fate of salt water that is transported through the locks into the Gatun and Miraflores Lakes as well as the long approach channel that is envisioned where the third lane will bypass the Pedro Miguel Lock and Lake Miraflores. The dispersion of this salt water is controlled by a number of processes. The most important are gravitational flow acting to draw the more dense, saltier water away from the forebays and vertical mixing that can eliminate the discrete bottom layer containing the saltier water. The vertical mixing results in part from the action of the wind and natural currents but probably more so from the passage of each ship as these occupy a significant part of the channel cross section. Because the flux of salt water to the lakes is small and the mixing due to the ships is significant, it is possible that mixing dominates in many circumstances. However, environmental damage may be more tied to the occasional situation where the flux of salt water is near its maximum while the vertical mixing is restricted. The differences between these conditions cannot be resolved using the volume-averaged Simulation Model.

The Simulation Model is an appropriate tool for developing a quantitative understanding of the processes that control the intrusion of salt water through the lock systems now, and for addressing the question of the relative behavior of the different proposed options for the Post-Panamax locks with respect to salt water intrusion and freshwater utilization. However, it is important to understand the sources of inaccuracy associated with an analysis based on this model. These primarily stem from the need to generalize important hydrodynamic processes and the need to ascribe patterns to the sequence of ships transiting the canal over periods of months or years.

Delft Report A does an excellent job of explaining the operation of the present series of locks. It also covers the data sets that were collected to properly understand the distribution of fresh- and salt-water in the different phases of the ship transits. These data were used to establish the empirical ‘exchange coefficients’ that are used to evaluate the fraction of the salt content of one lock basin that is transferred to the adjoining basin as the lock gates open and close. In actuality, the processes that cause this salt flux (discharge) are a complex combination of individual mechanism and effects. The exchange coefficient quantifies the overall effect. However, the data show that there are different coefficients for different size ships and that details such as the length of time the lock gates remain open also cause differences. To avoid developing a huge population of exchange coefficients to cover all possible situations it is

necessary to group the situations into general classes (eg. medium size ship moving quickly between the middle and upper Atlantic locks during an up-locking). Clearly, there are still a large number of situations and a correspondingly large set of coefficients. Each coefficient is merely the best estimate of an average value with an inherent error. Because the ships do not neatly divide into discrete displacement intervals these coefficients are probably more in error for vessels with sizes close to the vessel classification boundaries. When simulations are conducted for 72 lock system transits per day over a period of simulated years the individual inaccuracies tend to accumulate into significant uncertainties. This is not necessarily a linear process wherein the inaccuracies add directly one upon the other. Instead, some add while others subtract leading to an increasing spread in the possible results. Such effects are best quantified with a formal error and sensitivity analysis.

The scale of the uncertainties of the exchange coefficients can be seen in the graphs from the Delft report (Report A) that are reproduced as Figure 2-3 a, b, c and d. Each of the four pages (a,b,c,d) are for different stages in the up-, and down-lockages. On these plots the upper and lower lines represent the theoretical maximum and minimum possible values for the exchange coefficients. The discrete points are the values derived from measurements and the bold dashed lines are the values used in the numerical model. In all cases there is considerable scatter in the values derived from measurements. In some cases there are only one or two of these points. Some of the points derived from the measurements lie above or below the corresponding theoretical maximum or minimum values, respectively. It is important to bear this information in mind when seeking to apply the results of the modeling to engineering or management decisions.

The exchange coefficient issue becomes of even more concern when the Simulation Model is applied to predicting the salt-water intrusion in the envisioned Post-Panamax lock systems. This is because these locks will be unique in their scale and operation. There is no opportunity to take measurement of the salt fluxes that can be used to derive the exchange coefficients. Delft is well aware of this difficulty. In the reports covering the Post-Panamax situations they point out that the most reasonable analogs to these envisioned larger locks are the present ones. They recognize that there are significant differences such as the geometry of the approach sections, locations of the inlets and outlets within the lock chambers, etc. These could cause an unknown amount of difference between the present and future locks. Delft carried out a limited amount of simulations using the Delft3D detailed time varying hydrodynamic model to explore some of these issues but, in the end, they relied most on the coefficients derived from the present situation to pick the exchange coefficient values for the operation of the large locks. In our opinion this is a reasonable approach. However, engineers and managers who will use the results of these modeling analyses need to be fully aware of additional errors and uncertainties that are introduced by the necessity of evaluating the exchange coefficients in this way.

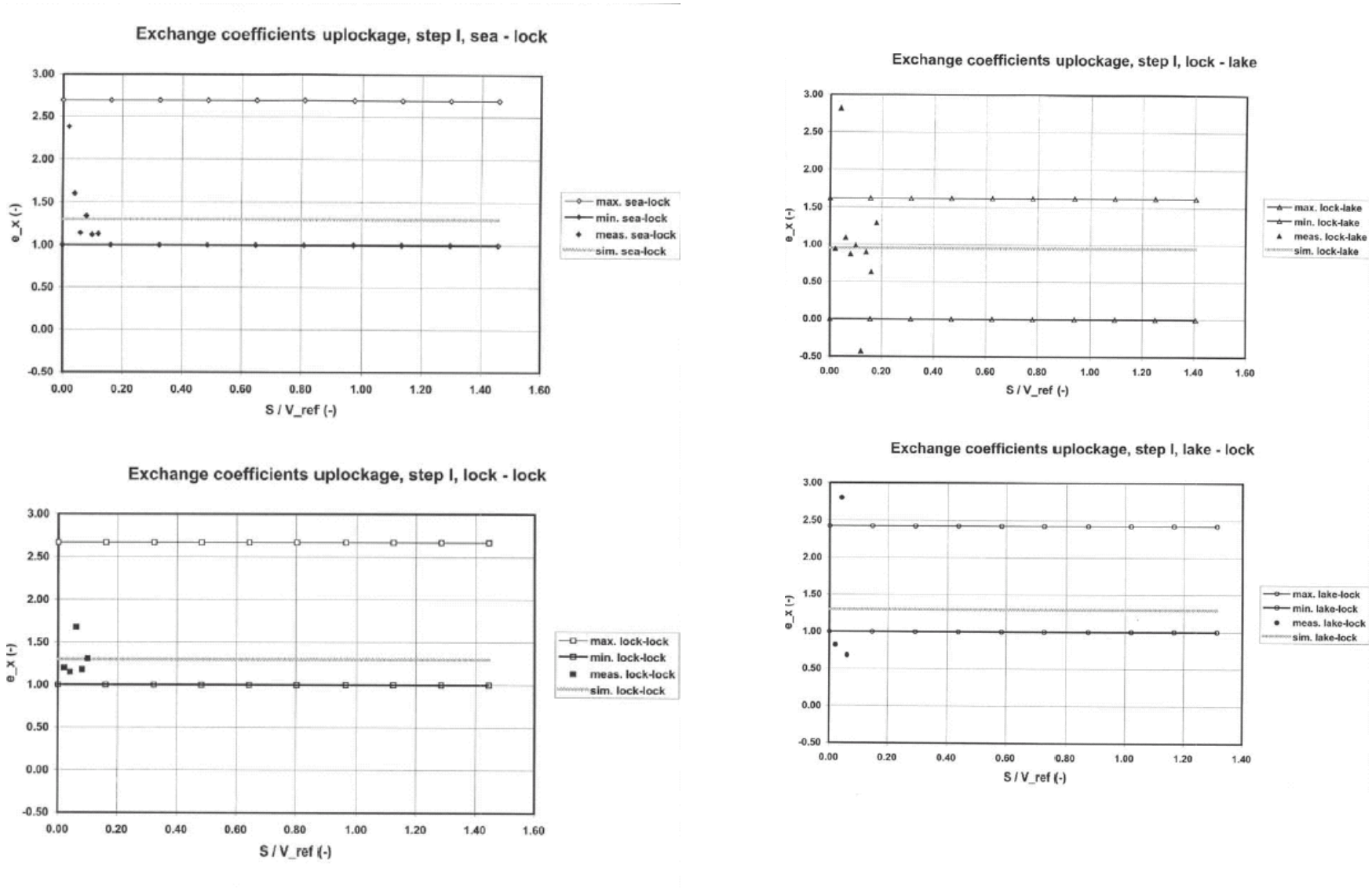
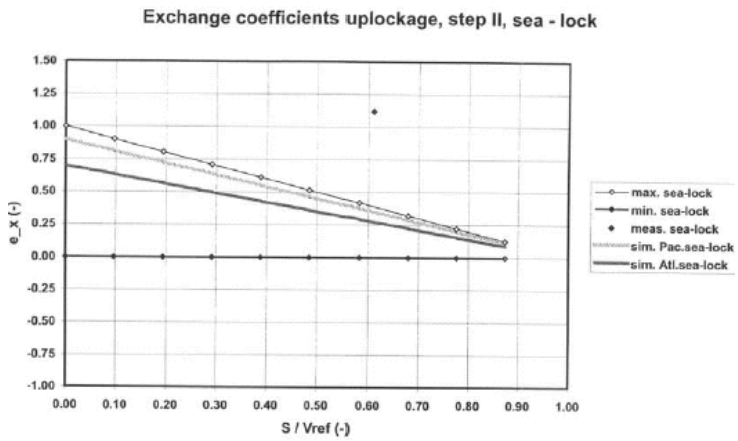
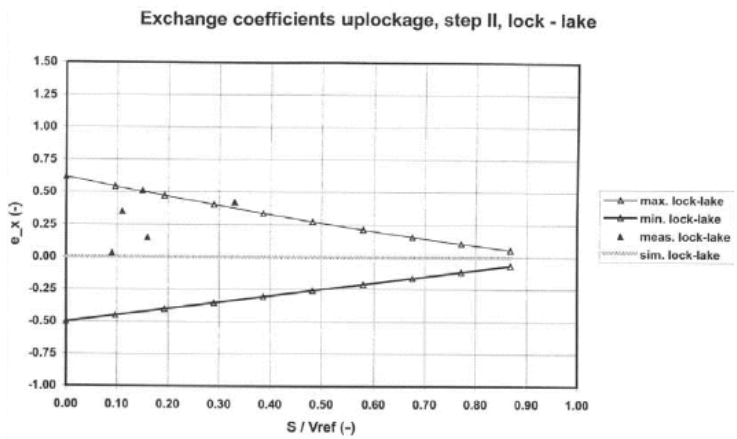
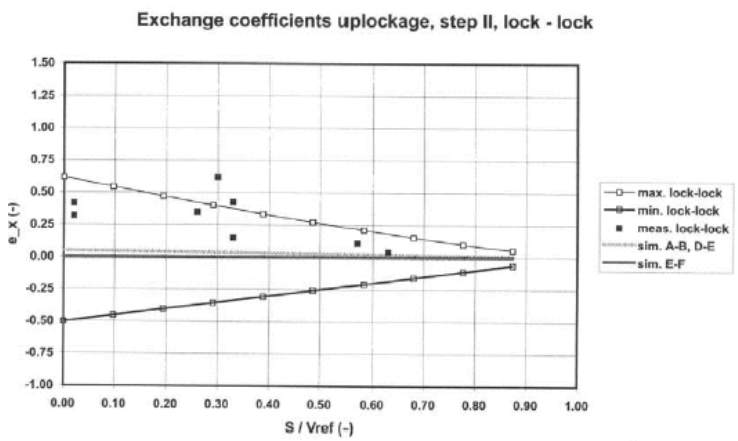


Figure 2-3a. Plots of measured (discrete points) exchange coefficients compared with the value used in the model (bold dashed line) for uplockage step 1 (redrawn from Delft Report A)







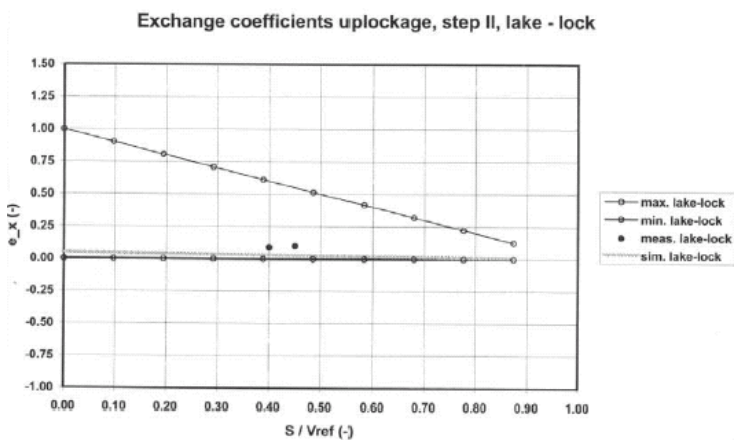


Figure 2-3b. Plots of measured (discrete points) exchange coefficients compared with the value used in the model (bold dashed line) for uplockage step 11 (redrawn from Delft Report A)

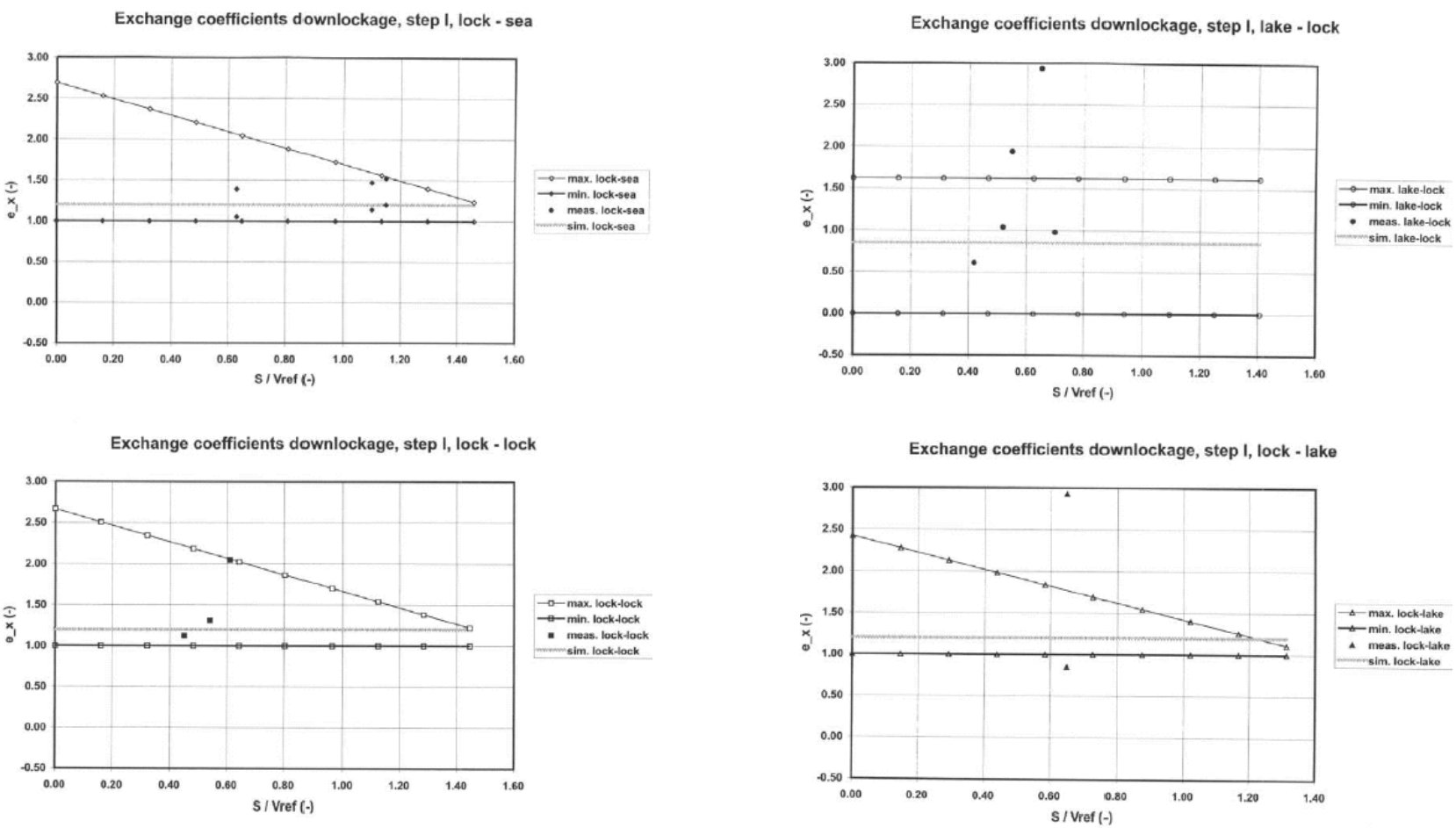


Figure 2-3c. Plots of measured (discrete points) exchange coefficients compared with the value used in the model (bold dashed line) for downlockage step 1 (redrawn from Delft Report A)

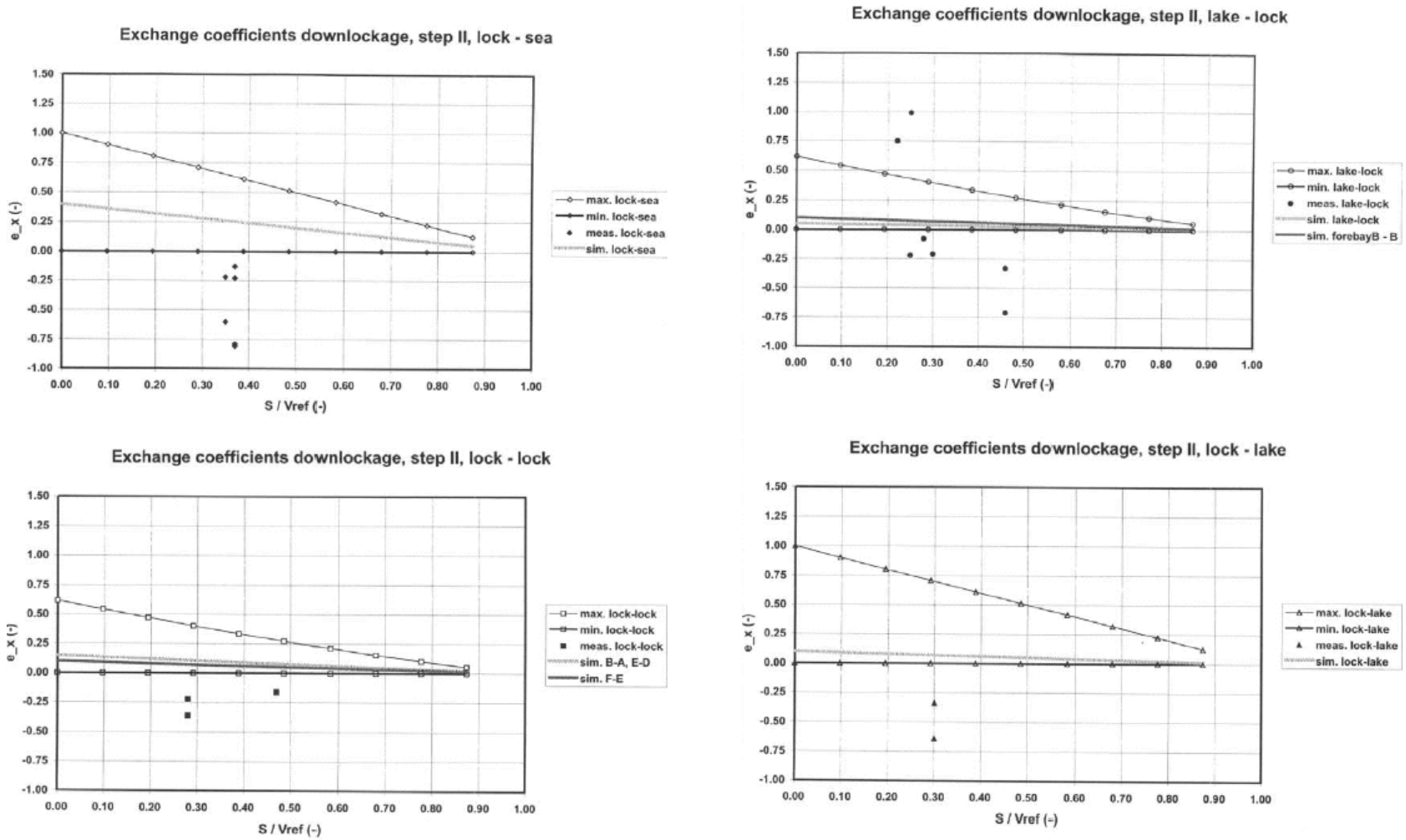


Figure 2-3d. Plots of measured (discrete points) exchange coefficients compared with the value used in the model (bold dashed line) for downlockage step 1 (redrawn from Delft Report A)

The analysis of the future conditions is subject to other assumptions as well. For example, it is assumed that the operation of the Post-Panamax locks will not change the discharges of freshwater at the Miraflores and Gatun dam spillways. Again, in the context of the present reports this is a reasonable assumption. Users of the model study reports need to be aware of these assumptions and how different the results would be if they prove to be unwarranted. It should be noted that two extreme representative scenarios where studied, one asssuming that the discharges are maintained, and the other minimizing the discharge from spillways to maximize the levels in the lakes. This last strategy is preferred by ACP and it is likely that it will be used during operation.

Another source of potential inaccuracy lies in the development of the ship traffic model scenarios and day patterns. Although these were provided by ACP on the basis of historical data and projected demand, in practice during the modeling, very little variability was introduced in the day-to-day (or simulated day-to-day) traffic. This may be a limit on the applicability of the results and these limitations are subtle.

The day pattern that was used to validate the Simulation Model analysis of current conditions was fixed for a 'typical' day while the model simulated durations of years (ie. many hundreds of days). Exchange coefficients and other model parameters were changed during the validation of the model for current conditions until the observed and measured salinity patterns in the lakes were in reasonable agreement. There appears to have been no attempt to determine whether some of the differences between initial model results and the measurements could have been better explained by differences between the ship traffic as it was input into the model and the actual ship traffic. This raises the potential for the changes in the other model parameters to have subsumed the impacts of these differences in the ship traffic. Although this could be an additional sources of error in the representation of the present conditions it might not be significant as it can be viewed as an error source that is offset by the other error sources.

However, it appears that the exchange coefficients for the lock operations were part of these adjustments during the validation phase of the analysis of current conditions. These may have been unknowingly passed along to the analyses of future conditions when the existing situation exchange coefficients were adopted for the future condition modeling. Considering all of the uncertainties associated with the modeling analyses of the future conditions this may, or may not have been a significant difficulty. Certainly users of the results should be aware of these concerns and this may be a subject that is worth revisiting in future work.

2.3 REVIEW OF MODEL APPLICATIONS AND PREDICTIONS

The Simulation Model has been applied to both the problem of quantitatively representing the present salinity intrusion conditions and to the predictions of these conditions when the third lane is added. Overall the representation of present conditions has been successful and many details have been learned about the processes that control the salinity fluxes through the lock systems.

Although the modeling of the present situation has been successful, we have some reservations about the methods. A principal concern is the scarcity of sensitivity analyses or other methods that objectively demonstrate that the choice of scenarios and model parameters has been optimized. It is possible, perhaps even likely, that such operations were conducted over the

course of the work by Delft and that these were simply left out of the reports for the sake of clarity. There is one set of sensitivity results given in Report D. Of the many parameters and coefficients in the Simulation Model only two were varied in these analyses. The results are shown in terms of the maximum and minimum salinities predicted in Miraflores and Gatun Lakes resulting from these variations. The maximum and minimum predicted values differed by about a factor of three for Miraflores and about a factor of two for Gatun Lake. This is a bit alarming given that there are a large number of other coefficients in the model.

This observation causes us to recommend that the results be used advisedly. The relative differences between the single-lift, double-lift and triple-lift options will almost certainly persist with other setting of the coefficients provided that the same values are used in all three analyses. However, the absolute results of the salinities in the lakes after the third lane is put in operation needs to considered advisedly. In our opinion it would be worthwhile to conduct additional sensitivity testing with the Simulation Model so that the limits, range, and central tendencies of the results can be quantitatively established.

Another issue to consider is whether the typical conditions or the extreme conditions are important in assessing the significance of predicted salinity levels in the lake after the canal expansion. Throughout the present reports, the work tended towards representing typical conditions for environmental, lock operation and ship traffic parameters. It is quite likely that while the typical values are of interest it will be the more extreme occurrences that are most concern for the lock design. For example, could there be a more severe and prolonged dry period that coincides with a particular sequence of ship traffic that combine to produce a period of salinities in Lake Gatun that are notably above the predicted typical dry season values? We believe that it would be worth conducting additional analyses to explore the potential for these untypical occurrences.

In the reports dealing with predicted salt water intrusion after the construction of the Post-Panamax locks there are uncertainties and limitations related to the selection of exchange coefficients. There are also uncertainties resulting from the ship traffic patterns that are assumed by the ACP; from the representations of the freshwater sources and releases, and from the representations of the inter-annual variability in rainfall.

We have also noted that the Simulation Model (alternatively named SWINLOCKS) is a good choice for quantitatively representing the processes controlling salt-water intrusion in the lock systems. It does poorly when representing the transfer of this salt water in Miraflores and Gatun Lake. Again, this affects the use and interpretation of the results. It is not clear that the validation of the Simulation Model with the field measurements fully respects the differences between volume-averaged and spot-measured values. More importantly, the salt entering Lake Miraflores probably flows away from the seaward locks as a discrete bottom layer some of the time. This may have more environmental impact than would be projected for well-mixed (volume-averaged) conditions. These issues could be readily addressed with additional field measurements and modeling. The modeling would combine the use of the Simulation Model with a three-dimensional time-varying hydrodynamic model. This would be especially useful when used in conjunction with the analyses of the extreme events described above.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

Overall, the Delft reports that have been reviewed cover work that has been competently and well done. The results are well supported and meaningful. However, engineers and managers who are to use these results need to be aware of the limitations of the modeling work. These limitations are discussed below. They certainly do not invalidate any of the results or conclusions of the Delft studies. But, these limitations can be significant in certain applications. We have made recommendations for additional work that will strengthen the overall effort.

3.2 RECOMMENDATIONS FOR FUTURE WORK

The series of Delft reports demonstrates the usefulness of the saltwater intrusion studies for verifying that the present operations are largely benign. They also show how information obtained from the present situation is important to predicting the effects of the Post-Panamax systems. These reason provide the justification for suggesting additional work.

In spite of the data that was collected in support of the Delft modeling studies and the additional data that has been previously collected, there is a need for additional measurements. One form of measurements would be with recording instruments so that the time-varying hydrodynamic parameters can be assessed. These are primarily temperature and salinity. The measurements are needed in the area just above the locks, certainly in Lake Miraflores and Lake Gatun. Where salinity is the parameters of concern these measurements would be best taken with recording instruments located at the bottom of the approach channels so that pulses of high salinity bottom water flowing away from the locks may be measured and then associated with particular ship sizes, lock operations, or other causes.

We also recommend that the Simulation Model be retained and strengthened for future applications. There is always the need for more data to support such modeling and surely WL|Delft could list measurements that are needed in, and near, the locks to better support the exchange coefficients or to expand the range of conditions that are parameterized. This work should be combined by a better method of classifying the vessels in order to significantly reduce the scatter of the values derived from measurements. That is, the present data strongly suggest that variables other than those presently used to distinguish between ship types contribute to the uncertainty in the results.

There appears to be an immediate need for additional sensitivity analyses to bind the reliability of the results of the modeling given in the present series of reports. These analyses should include both the model parameters, certainly including the exchange coefficients, as well as the representations of vessel traffic.

A modeling effort that combines the Simulation Model for saltwater intrusion through the locks needs to be combined with a more detailed representation of the flow in the approach channels above the locks using a three-dimensional time-varying model. Such an effort is well within the state-of-the-art. It would profit from the additional field measurements recommended above. This effort would result in a much more detailed and valid prediction of future conditions once it had been verified for the present situation. It would also permit

assessment of possible low cost ways of further reducing the effects of the third lane of the salinity regime of Lake Miraflores.

The combination of the Simulation Model and time-varying hydrodynamic model would be an excellent way of assessing the potential for uncommon (not necessarily extreme) conditions to develop under certain combination of season weather and ship traffic. Such an analyses is needed to appropriately describe the current situation and to make useful predictions of the environmental impacts of the envisioned third lane.

The primary use of the time-dependent model would be to analyze and predict the fate of salty water that is released into Miraflores and Gatun Lakes as a result of the present and future lock operations. URS does not propose to substitute the Delft SimLocks model. This model is a practical and adequate tool for representing the transfer of salinity as a result the lock operations. We do feel that SimLocks will benefit enormously from additional measured data, a refinement of the parameterization of the effects of different ship sizes and lock operation patterns to reduce the scatter in the ‘exchange coefficients”, and some formal sensitivity analyses.

Assuming that these improvements are made to SimLocks then it can provide an essential starting point for modeling of the fate of salinity transported to the lakes by the present and future locks. It would be best to start this work in conjunction with the updating and improving of SimLocks because it would be convenient to use the outputs from SimLocks as inputs to the time-dependent model. However, it would be wise to examine the possibility of eliminating the ‘artificial forebay’ segments and take the results of each simulated lock operation as output directly from the upper lock chamber node rather than the present output point. This doesn’t mean that the “forebay’ nodes need to be deleted from SimLocks. They are vital to the operation of that model.

The point of interaction between SimLocks and the time-dependent model needs to be defined after some detailed discussions with the Delft modelers. In all cases this interface is located at the boundary of the lock and lake regimes. On the Atlantic side this is the region of the upper lock and Lake Gatun. On the Pacific side this would be either, or both of the upper lock with Lake Gatun and the Second Lock and Lake Miraflores. The candidates for the specific points in the numerical model for these special outputs are from one of three places: a) the point of discharge and intake to the node representing the upper lock, b) directly from the node representing the forebays, or c) at the output of the forebays.

Once this is decided, the time series output of SimLocks should appear as a series of discharges (and intakes) between the locks and the immediately adjoining portion of the lakes. This would be the upstream boundary of the time-dependent model. The time-dependent model would have a three-dimensional gridded domain that would represent the lakes from where they interface with the locks to distance “well beyond the maximum extent of the salt-influence”. That is to say that, with the exception of Miraflores, it should not be necessary to show all of Gatun Lake in the model grid. To save computation time and effort the model domains would extend a predetermined distance from the locks. So there would be three grids. One for Lake Miraflores. The other two would cover the Atlantic and Pacific portions of Gatun Lake. The extent of these two model domains would need to be determined from measurements or through adjusting original domains; making them larger or smaller based on the initial results.

In operation the three-dimensional time-dependent model (3D/T-D model) would be forced by time-series of discharges into and from the locks. These 'pulses' would contain the volume-averaged salt concentrations. Flow in the 3D/T-D model would be driven (forced) by internal factors such as relative densities of the water pulses and turbulent mixings as well as external factors such as wind stress acting on the surface and bottom friction. Sources and sinks (outlets) of water would also be included.

The point of the model would be to make realistic simulations of canal operations representing periods of many months to several years. Day-to-day differences in ship traffic, weather and seasonal conditions would be included. The output would show the details of the penetration of salt water plumes into the lakes, especially along the bottom. These outputs could then be summarized in statistical representations of the occurrence of different salinity levels at different distances from the locks and at different water depths.

It would be best to have a series of actually measured flow and salt-concentration measurements that could be use to calibrate, test and verify this model.

When the model has been shown to properly simulate the measured data it would be used to predict time-varying conditions in the future when the Post-Panamax lanes are put in operation. Again, this model would be set-up and operated in conjunction with the (upgraded) SimLocks model. This combination would be very powerful tool in the evaluation and final design of one of the concepts for the Post-Panamax lock systems.

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