STUDY OF ADDITIONAL COMBINATIONS OF LOCKS WATER SAVING BASINS FOR PROPOSED POST-PANAMAX LOCKS AT THE PANAMA CANAL

FINAL REPORT

**Photos Taken of Bachhausen and Hilpolstein Locks near Nurnberg, Germany (by INCA)*

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EXECUTIVE SUMMARY

The Autoridad Del Canal De Panama (ACP) is conducting a study of the Panama Canal to evaluate the feasibility of constructing facilities and features to augment the Canal's capacity and capability to transit vessels. The proposed locks (~61m x 457m x 18.3m– 200' x 1500' x 60') will be significantly larger than the existing locks (33.5m x 305m x 13m – 110' x 1000' x 43'), and with the addition of these new larger locks, water demands from Gatun Lake are expected to increase dramatically. In fact, ACP estimates that the water volumes required by the new locks could approach 2.6 – 7.7 times the current lock volumes based on preferred new lock configurations. In light of the above, and coupled with the fact that operation of the current locks, municipal water consumption, hydropower generation, occasional spillage, and evaporation cause seasonal water level changes of up to 2.5 m (9') in Gatun Lake, a conceptual study for the design of new locks equipped with water saving basins was warranted.

However, the results of this study showed that the lock and water saving basin wall heights needed to meet the theoretical water saving percentages under the full range of water levels and lockage lengths were quite high. As a partial result of these substantial lock and basin wall heights, the total opinions of probable costs for the systems ranged from $357 million to $573 million which exceeded the ACP desired budget for the project. Furthermore, the preliminary study also showed that a stacked basin arrangement with placement of basins to only one side of the lock necessitated an "overlap" between the basins that could not be overcome if the theoretical water saving percentage was to be achieved always.

Based on the above findings of the preliminary conceptual study for the design of new locks' water saving basins, ACP commissioned an additional study with the goal of reducing the necessary lock and basin wall heights in hopes of reducing overall project costs. The purpose of this study is to investigate different alternatives for lock and water saving basin configurations and to design them for a smaller range of water levels and lockage lengths that occur most often. Specific lake and tide level combinations in addition to a single lockage length of 457.2 m (1500') would be used to set required lock and water saving basin floor elevations and wall heights, but the full range of lake and tide levels would be used to investigate the possible impacts (water spillage, additional water usage, etc.) of not designing for all operational conditions for the hydraulic analyses. More detailed sensitivity analyses would also be performed on the Pacific Ocean side to determine the effects of allowing the system to handle a wider range of operating conditions, as well as probabilistic analyses for the multi-lift options on the Pacific Ocean side to further optimize lock and basin wall height design.

The study options for this new work order were:

- OPTION 1 – Three-lift lock structure – side-by-side water savings basins to one side of lock – 50% water savings – Atlantic and Pacific Ocean sides,
- OPTION 2 – Three-lift lock structure – side-by-side water savings basins to one side of lock – 60% water savings – Pacific Ocean side only,
- OPTION 3 – Two-lift lock structure – side-by-side water savings basins to one side of lock – 50% water savings – Atlantic and Pacific Ocean sides, and

- OPTION 4 – One-lift lock structure – stacked water savings basins on both sides of lock – 75% water savings – Atlantic and Pacific Ocean sides.

As part of the study, a comprehensive data collection was completed along with a formulation of detailed design criteria. These criteria and design procedures were applied to determine basin and conduit layouts and associated sizes. These features were then conceptually designed hydraulically, structurally and geotechnically for Options 1 and 4.

As in the previous work order, an in-house spreadsheet model was used to complete the hydraulic analyses. This model was checked against the USACOE's LOCKSIM model and calibrated/verified to the existing locks with satisfactory results. A preliminary design of the lock Filling and Emptying (F/E) culverts (for Option 4 – the results from the previous work order were used for Option 1) was also completed to determine reasonable head loss estimates at the interface of the two systems and more importantly to determine the upper threshold of WSB conduit size (i.e., the WSB conduit should not be larger than the lock F/E culvert).

Hundreds of individual model runs were completed to create parametric curves which provided an opportunity to investigate "what-if" scenarios with a range of culvert sizes and arrangements. These curves were also plotted against the two most important design criteria which were equalization time and instantaneous maximum F/E rate. The explicit criteria for the lock F/E culverts were:

- the instantaneous maximum F/E rate should not exceed 2.28 m/min (7.5 ft/min) (the maximum for the existing locks with two culvert operations), and

- F/E times for a 3-lift system should be 8 – 9 min per lift (based on the existing system) and for a two-lift system, (3 lift x 8 – 9 = 24-27 min total)/2 lift = 12 – 13.5 min/lift. A factor of 3/2 was used to compute the F/E time for a two-lift system, assuming equal total operational times for the three-lift and two-lift systems. This factor was used only as a target in designing the preliminary F/E system.

In applying these criteria, the finalized lock F/E culvert sizes were found to be:

- Option 1– Atlantic Side (8.84m - 29'),
- Option 1 – Pacific Side (8.53m - 28'), and
- Option 4 – Pacific Side (6.40m - 21').

Parametric curves were also created for the design of the water saving basin conduits. The design criteria for the WSB conduits were:

- the WSB conduits should not be larger than the preliminary F/E culvert sizes,
- no conduit solution should exceed an instantaneous maximum F/E rate of 2.28 m/min (7.5 ft/min) for basin to lock operations, and
- no conduit solution should have a single basin operation time of less than 2 minutes (which is the assumed shortest time needed to open and immediately close the valves).

Using these criteria, a myriad of solutions were available so methodologies were formulated to combine the results from the lock F/E culvert and the WSB conduit analyses to compute more meaningful statistics including total operation time, allowable transits/day, etc.

These results were then reviewed. Based on the selections from the previous study by ACP, the finalized WSB conduit arrangement and sizes chosen for illustrative purposes were:

- Option 1 – Atlantic Side - 4 conduits/basin (6.10m - 20'),
- Option 1 – Pacific Side - 4 conduits/basin (6.10m - 20'), and
- Option 4 – 4 conduits/basin (6.71m - 21').

The selections of the number and sizes of conduits for the above options were mainly based upon the selections made by ACP for the previous work order which were based upon the desire to obtain a range of price scales for the different options. Therefore, the conduit selections should be viewed as preliminary and for illustrative purposes only.

Throughout the conceptual design process, it became apparent that by designing the locks and water savings basins' system for a narrower range of hydrologic and hydraulic conditions, the required lock and basin wall heights would be substantially reduced. This conclusion is based on a comparison of lock and basin wall heights for Options 1-3 in this study to similar configurations (i.e. equivalent number of locks and overall percentage savings) studied in Work Order No. 1. The results of the comparisons are summarized in **Tables VII.1** and **VII.2**.

As shown in **Tables VII.1 & 2**, the percent reduction in **lock wall heights** ranged from approximately 5–10 %, while the percent reduction in **basin wall heights** was more significant, ranging from approximately 30-60 %. It should be noted that some percentage of the wall height reduction for the locks can be attributed to the exclusion of the 2 ft sill in this study. It should also be noted that a significant portion of the **basin** wall height reductions can be attributed to designing for only one lockage length (1500') versus three (1400', 1500', 1600'). In fact, it is very likely that this factor (which was applied to **each** lock level for Work Order No. 1) has a much more direct impact on required basin wall heights versus the water level variation effects which would be split among all locks.

An additional comparison made for Options 1-3, related to the limitation of hydrologic and hydraulic conditions designed for in this work order, was that of water usage. The results of the comparisons are summarized in **Table VII.3**.

As shown in **Table VII.3**, the overall trend is an increase in the water volume taken from the lake between Options 1-3 in this study and the corresponding options from the previous study. In fact, the Atlantic side Work Order No. 2 options require approximately **12%** more water volume than similar options designed under Work Order No. 1. This lost water volume equates to approximately 2 lockages a day (based on a current operating total of 16 lockages/day) or 700 lockages/year. The volumetric increase occurs as a result of the fixed lower lock equalization elevation set in this study (which in turn also lowers the required lock and basin wall heights).

Please recall that in the previous work order, the system was designed to meet all lake and tide elevations, so that there was no water spilled. The system was designed to fully handle all possible equalization levels based on the full range of lake and tide levels as well as lockage lengths. In this study, the forcing of a fixed lower lock equalization elevation requires the system to spill water under conditions where the lake and/or tide elevation result in lower lock equalization elevations which are higher than the fixed equalization elevation. Another consequence of these occurrences is that the upper and middle (where applicable) locks' elevations are lower than would exist if the system were allowed to achieve the theoretical equalization elevation (i.e. no spillage). Since these elevations are lower (artificially depressed by the fixed lower lock TOWSE), the lake must supply more water for the upper lock(s) operations.

As also shown in **Table VII.3**, the percent increases in water usage between the current and previous studies are higher for the Atlantic Ocean side options (~12% average) as compared to the Pacific Ocean side options (~3% average). This occurs because the chosen lower lock top of operating water surface elevations (TOWSE) for Options 1-3 on the Pacific Ocean side (based upon the ACP selections from the probabilistic analyses) are higher than those chosen from the hydraulic analyses where the theoretical TOWSEs were set using a lake elevation of 81.0 ft and the low tide elevation (-7.6 ft PLD). The higher elevations result in less water spilled overall (and a greater range of lower lock equalization elevations accommodated) and also decrease the volume of water taken from the lake. For the Atlantic Ocean side options (Options 1&3), the TOWSEs were set using a lake elevation of 81.0 ft and the low tide elevation (-1.25 ft PLD), since the sensitivity and probabilistic analyses were not required by ACP for these options. However, if a similar probabilistic analysis had been completed for the Atlantic side options and ACP had allowed for a increased lower lock TOWSE elevation (as was done for the Pacific side), the percent increase in water usage for the Atlantic side options would have decreased also.

The single lift, stacked basin arrangement (Option 4) with basins on both sides of the lock will eliminate the problem of overlap addressed in Work Order No. 1. The basins are arranged so that they are offset from one side to the other. On the Pacific Ocean side, it was necessary to increase the width of the basins (m>1.0) to a value greater than that of the locks to eliminate overlap. The m-factor by which the overall basin areas were increased was calculated as 1.21. This results in a 16 m (52.5') increase in the basin width from the typical basin width of 76.2m.

The results of the hydraulic analyses are summarized and compared for all options in the following tables. The volumes presented in the tables are per lockage.

System Layout and Theoretical Water Savings Percentages for all Options

OPTION	# Lifts	# WSBs per Lift	# Conduits per WSB	Conduit Diameter	Theroretical Water Savings Percentage
Option 1	3	2	4	6.10 m (20')	50%
Option 2	3	3	#N/A	#N/A	60%
Option 3	2	2	#N/A	#N/A	50%
Option 4	1	6	4	6.40 m (21')	75%

Overall Water Usage and F/E Times per Lockage for Atlantic Side Options

Metric Units

OPTION	Water Intake Volume With Basins (thousand m^3)			Water Spillage Volume With Basins (thousand m^3)			% Water Savings With Basins			Avg. Total F/E Time per Lockage (min)
	min	mean	max	min	mean	max	min	mean	max	
Option 1	115.4	118.3	130.2	0.0	12.1	27.0	46.1%	49.1%	50.0%	32.68
Option 2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Option 3	169.4	177.4	202.3	0.0	7.9	40.8	46.8%	49.5%	50.0%	#N/A
Option 4	164.1	185.4	188.5	0.0	0.0	0.0	74.3%	74.9%	75.0%	#N/A

English Units

OPTION	Water Intake Volume With Basins (million gal)			Water Spillage Volume With Basins (million gal)			% Water Savings With Basins			Avg. Total F/E Time per Lockage (min)
	min	mean	max	min	mean	max	min	mean	max	
Option 1	30.48	31.25	34.41	0.0	3.20	7.12	46.1%	49.1%	50.0%	32.68
Option 2	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Option 3	44.74	46.88	53.44	0.0	2.08	10.77	46.8%	49.5%	50.0%	#N/A
Option 4	43.36	48.98	49.79	0.0	0.0	0.0	74.3%	74.9%	75.0%	#N/A

Overall Water Usage and F/E Times per Lockage for Pacific Side Options

Metric Units

OPTION	Water Intake Volume With Basins (thousand m^3)			Water Spillage Volume With Basins (thousand m^3)			% Water Savings With Basins			Avg. Total F/E Time per Lockage (min)
	min	mean	max	Min	mean	max	min	mean	max	
Option 1	101.0	121.5	156.8	0.0	4.2	40.0	39.3%	50.0%	50.0%	32.68
Option 2	77.7	96.2	131.7	0.0	0.2	18.6	49.1%	59.9%	60.0%	#N/A
Option 3	147.0	182.5	219.6	0.0	4.9	44.7	39.2%	50.0%	50.0%	#N/A
Option 4	137.2	171.5	188.5	0.0	0.0	0.0	75.0%	76.2%	76.7%	32.52

English Units

OPTION	Water Intake Volume With Basins (million gal)			Water Spillage Volume With Basins (million gal)			% Water Savings With Basins			Avg. Total F/E Time per Lockage (min)
	min	mean	max	min	mean	max	min	mean	max	
Option 1	26.69	32.10	41.43	0.0	1.10	10.56	39.3%	50.0%	50.0%	32.68
Option 2	20.54	25.42	34.81	0.0	0.06	4.91	49.1%	59.9%	60.0%	#N/A
Option 3	38.84	48.22	58.01	0.0	1.30	11.80	39.2%	50.0%	50.0%	#N/A
Option 4	36.25	45.30	49.81	0.0	0.0	0.0	75.0%	76.2%	76.7%	32.52

As stated previously, by designing for a smaller range of water levels and lockage lengths, the required lock and basin wall heights were considerably reduced for this work order when compared to the results of the previous work order. However, this benefit is not without serious consequences. For one, these options will require considerably more water from the lake over time than the systems designed for Work Order No. 1. Also, there may be safety and possible downtime issues with this revised system as now overfillage of locks and basins will be a real concern since the full range of lake and tide levels as well as lockage lengths are not being accommodated in this new design. It is true that the cost of the basins will now be lower, but necessary spillage and possibly recirculation systems may nullify this cost savings in the long run especially if one also includes the likelihood of lost time due to accidents (overfillage) that may occur even with elaborate "fail-safe" control systems in place. It should also be noted that the footprint reduction that was incorporated in this work order (bringing the basins closer to the locks by fitting the first in between the gate recesses) could also be applied to the previous work order arrangements for a considerable cost savings which may also make them economically viable. Finally, as can be seen in above tables, with these new systems, the target water savings percentage is not always achieved. In fact, when the lake levels are the lowest (below 81.0'), the water savings percentage is at its worst given that the WSB's were designed to fully operate at lake levels of 81.0' and higher.

In conclusion, Option 2 consumes the least water and spills the least water, but would likely be the most costly option given the number of lifts and basins. Options 3 and 4 consume similar

volumes of water, but cost differentials are hard to estimate given the complexity of constructing a single-lift, six stacked basin arrangement (Option 4) versus a two-lift, two side-by-side basins arrangement (Option 3). Option 1 falls in the middle as far as water usage and would also likely fall in the middle of comparative total costs. Therefore, weightings of costs, overall water usage, lock operating characteristics, safety, maintenance, and vessel throughput goals should be considered when deciding which options warrant further investigation.

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I. PROJECT PURPOSE AND SCOPE

A. Introduction

The Autoridad Del Canal De Panama (ACP) is conducting a study of the Panama Canal to evaluate the feasibility of constructing facilities and features to augment the Canal's capacity and capability to transit vessels. As part of this work, ACP recently began a study for the conceptual design of new locks capable of transmitting Post-Panamax ships through the Panama Canal Area (see **Figure I.1**). The proposed locks (~61m x 457m x 18.3m– 200' x 1500' x 60') will be significantly larger than the existing locks (33.5m x 305m x 13m – 110' x 1000' x 43'), and with the addition of these new larger locks, water demands from Gatun Lake are expected to increase dramatically. In fact, ACP estimates that the water volumes required by the new locks could vary from 2.6 to 7.7 times the current lock volumes dependent upon the new lock configuration. In light of the above, and coupled with the fact that operation of the current locks, municipal water consumption, hydropower generation, occasional spillage, and evaporation cause seasonal water level changes of up to 2.5 m (9') in Gatun Lake, a conceptual study for the design of new locks equipped with water saving basins was warranted. Therefore, ACP commissioned Moffatt & Nichol Engineers (M&N) in association with INCA Engineers and Golder Associates to complete a conceptual study for the design of new locks equipped with water saving basins. The goal of this study was to investigate various alternatives for lock and water saving basin configurations which were to be designed to provide theoretical water saving percentages under all operating conditions (both in varying water levels – lake and tide – and varying lockage lengths). However, the results of this study showed that the lock and water saving basin wall heights needed to meet the theoretical water saving percentages under the full range of water levels and lockage lengths were quite high. As a partial result of these substantial lock and basin wall heights, the total opinions of probable costs for the systems ranged from $357 million to $573 million which exceeded the ACP desired budget for the project. Furthermore, the preliminary study also showed that a stacked basin arrangement with placement of basins to only one side of the lock necessitated an "overlap" between the basins that could not be overcome if the theoretical water saving percentage was to always be achieved.

Figure I.1 - Panama Canal Area Location Map

B. Study Purpose

Based on the findings of the preliminary conceptual study for the design of new locks' water saving basins, ACP commissioned Moffatt & Nichol Engineers and INCA Engineers to begin an additional study with the goal of reducing the necessary lock and basin wall heights in hopes of reducing overall project costs. The purpose of this study is to investigate different alternatives

for lock and water saving basin configurations and to design them for a smaller range of water levels and lockage lengths which occur most often. The alternatives for lock and water saving basin configurations include one, two, and three lift locks with water saving basins (both side-by-side and stacked) on one or both sides. Specific lake and tide level combinations in addition to a single lockage length of 457.2 m (1500') would be used to set required lock and water saving basin floor elevations and wall heights, but the full range of lake and tide levels would be used to investigate the possible impacts (water spillage, additional water usage, etc.) of not designing for all operational conditions for the hydraulic analyses. More detailed sensitivity analyses would also be performed on the Pacific Ocean side to determine the effects of allowing the system to handle a wider range of operating conditions, as well as probabilistic analyses for the multi-lift options on the Pacific Ocean side to further optimize lock and basin wall height design.

C. Canal System Description

As stated above, the evaluation of the proposed Post-Panamax locks must address important issues such as water availability. Operating the new locks will create a future demand for water from Gatun, Madden, and Miraflores Lakes that must compete with future municipal, industrial and other demands from Panama's growing economy and population. With numerous studies already being carried out by ACP to identify new water supplies to supplement those already in use, it becomes crucial to conserve the water resources available. Therefore, it is imperative that ACP has a detailed understanding of the water savings versus cost issues for various water saving basin system alternatives so that informed decisions can be made about the best options available for further study and possible implementation. However, in order to begin the process, an understanding of the existing system is vital.

On the Atlantic side, Gatun Locks raise and lower ships between the Atlantic Ocean and Gatun Lake in three consecutive lifts. Lock operations are supplied using freshwater from Gatun Lake. The average tide range on the Atlantic side is approximately 0.2 m (0.7') while the maximum tide range is ~1 m (3.3'). The average water level in Gatun Lake is 25.9 m (85.0') above PLD (Precise Level Datum), but the lake level can vary between 23.9 m (78.5') to 26.7 m (87.5').

On the Pacific side, Miraflores Locks raise and lower ships between the Pacific Ocean and Miraflores Lake in two lifts using freshwater from Miraflores Lake (and ultimately, Gatun Lake). The average tide range on the Pacific side is approximately 3.8 m (12.6') while the maximum tide range is ~7.0 m (23.1'). The average water level in Miraflores Lake is 16.5 m (54.0').

The Pedro Miguel locks are used to raise or lower ships between Miraflores and Gatun Lakes using only freshwater from Gatun Lake. For plan and profile views of the existing system, see **Figures I.2** and **I.3**.

Operationally, the ACP runs uplockages (ocean to lake – raising the ship) and downlockages (lake to ocean – lowering the ship) in varying time increments as a function of transit scheduling. Therefore, the new locks and water saving basin system must be designed to work under a varying range of conditions that can change from performing uplockages to downlockages very quickly.

Figure I.2 - Satellite Image of Panama Canal Area (Taken from CZ Brats Website)

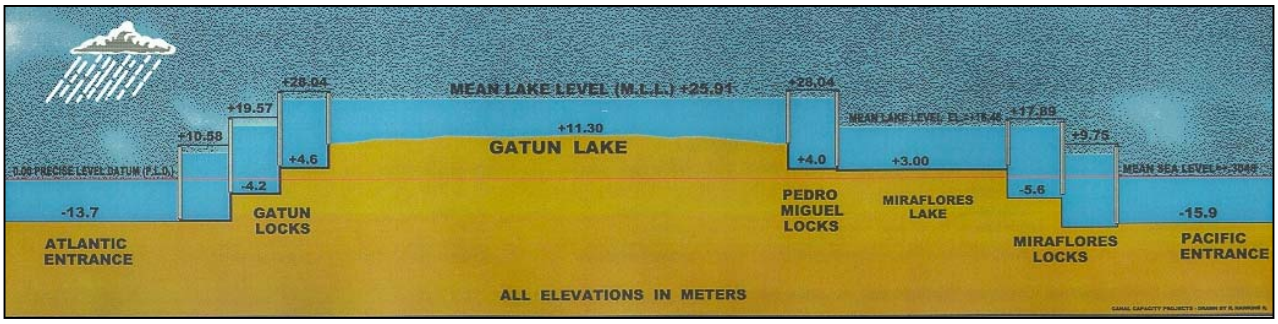


Figure I.3 - Profile of Existing System (Provided by ACP)

As one can see from the above range of lake and tide levels, the range of equalization levels within the locks and water saving basins will be related to hydrologic conditions in Gatun Lake and to tide elevations in the ocean. Consequently, the conceptual design of the locks water saving basins requires a detailed analysis that accounts for these differing water levels and their effect on equalization levels. Of particular concern will be the larger tide range on the Pacific side, which requires the new locks and water saving basins to operate and equalize under a much wider range of elevations than on the Atlantic side.

D. Water Saving Basin Operation – Conceptual Description

Consider the simplest case of a single-lift lock (see **Figure I.4**). For a ship to pass from the high level to the exit level, the lock is sequentially filled and emptied using source water from the high-level water body. Each locking operation consumes a volume of water equal to the lift times the surface area of the lock or in this case (100 – 0) * A = 100A.

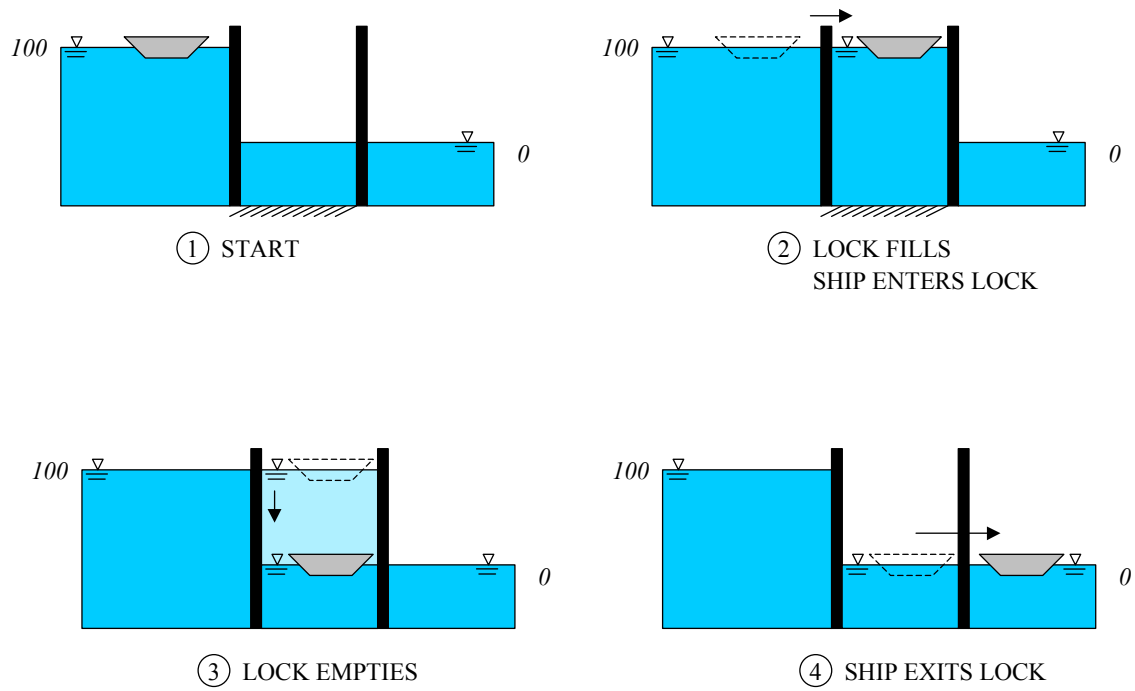


Figure I.4 – Typical Downlockage Operation for a Single Lift Lock

If conserving water becomes an important goal, then it is feasible to equip the lock with holding basins that are placed to either or both sides of the lock. The basins can be connected to the main lock filling/emptying system through a standard culvert and valve system such as is used for lock-to-lock operations. For simplicity, assume that the basins have the same surface area as the lock. Consider again the single lift lock already described above, now fitted with two water saving basins as shown in **Figure I.5**. For the system to function entirely under gravity flow, the geometry must be set so that the lift of the lock is vertically segmented into n+2 parts, where n is the number of basins. Therefore, in the example, the lock lift comprises 4 –25 unit slices.

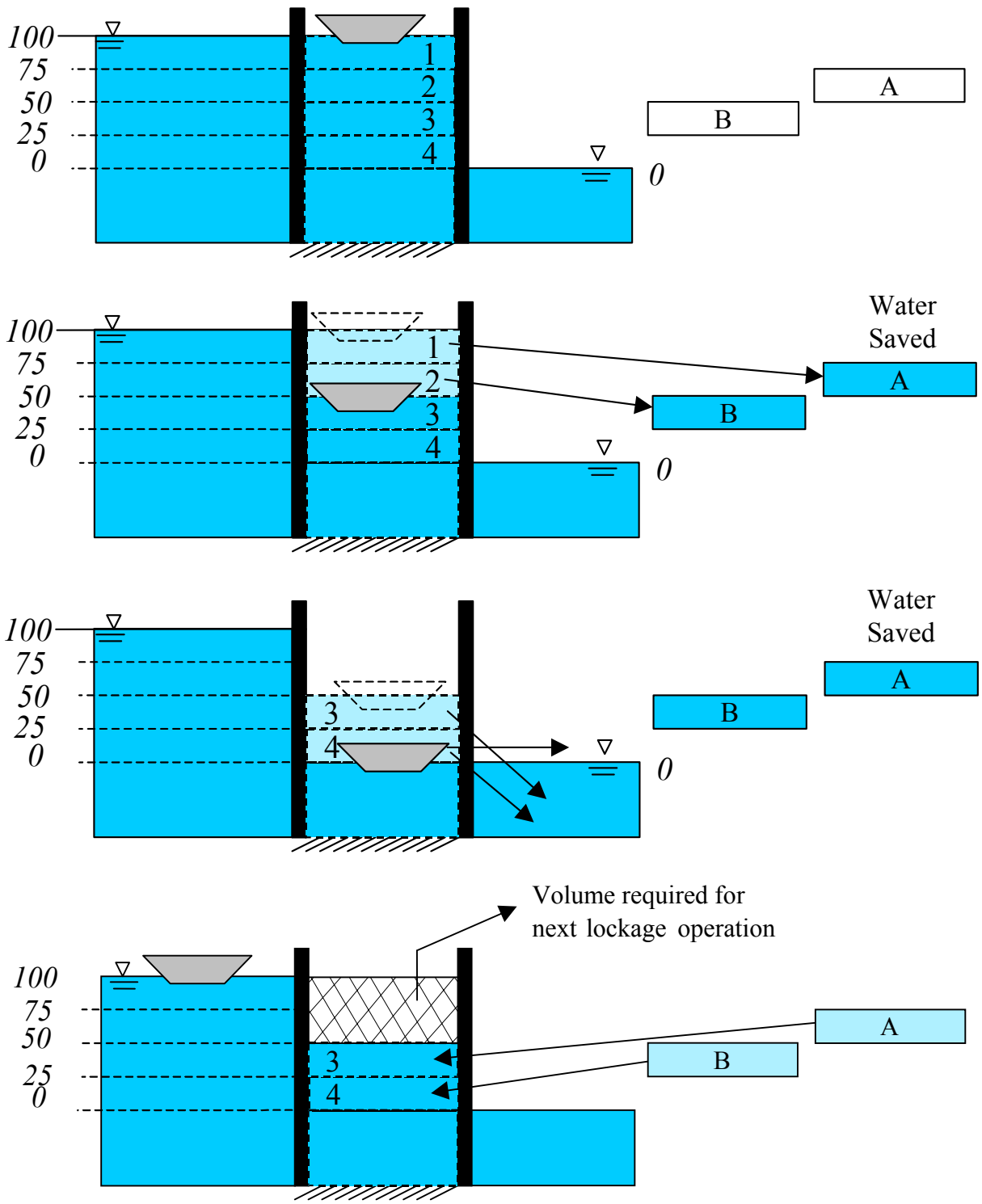


Figure I.5 – Typical Water Saving Basin Operation

In an emptying operation, the lock is drained sequentially into Basin A, followed by Basin B. This saves the lock water from Segments 1 and 2. Finally the water in Segments 3 and 4 is drained to the receiving water body to complete the emptying operation. When refilling the lock, the water in Basin B is drained to Segment 4, and then Basin A is drained to Segment 3. Segments 1 and 2 are filled using makeup water from the higher source water body. In this way, 50% of the volume of water is conserved. In general terms, it can be shown that the theoretical water savings is n/(n+2) – (n is the number of basins) when the basin surface area is equal to the lock surface area. It follows then, that three basins would yield a potential savings of 60% (3/5), while four would save 67% (4/6).

E. Project Scope

The project scope considers several different lock and water saving basin configurations aimed at determining an optimized solution which maximizes water savings while minimizing lock and basin wall heights and associated costs. Specific tasks to be completed include:

- Project Work Plan and QA/QC Plan,
- Design Criteria,
- Study of Lock and Basin Alternatives,
- Design and Layout of Study Alternatives (Including hydraulic, sensitivity, and probabilistic Analyses),
- Features Layout and Design (Options 1 & 4 only)
- Presentation of Analyses, and
- Associated Reports and Meetings Necessary to Complete the Work.

The alternative layouts included within the study were the following:

- OPTION 1 - Three-lift lock structure – side-by-side water savings basins to one side of lock – 50% water savings – Atlantic (hydraulic analyses only) and Pacific Ocean (hydraulic, sensitivity, and probabilistic analyses) sides,
- OPTION 2 - Three-lift lock structure – side-by-side water savings basins to one side of lock – 60% water savings – Pacific Ocean (hydraulic, sensitivity, and probabilistic analyses) side only,
- OPTION 3 - Two-lift lock structure – side-by-side water savings basins on one side of lock – 50% water savings, Atlantic (hydraulic analyses only) and Pacific Ocean (hydraulic, sensitivity, and probabilistic analyses) sides, and
- OPTION 4 - One-lift lock structure – stacked water savings basins on both sides of lock – 75% water savings –Atlantic and Pacific Ocean (hydraulic and sensitivity analyses) sides.

Based on the findings of the study of the lock and basin alternatives, specific configurations for each option were selected for design and layout. A full concept design including preliminary sizing of culverts, basins, and operating machinery, and development of component and system operating times was performed for Options 1 and 4.

M&N was responsible for the overall project management, the conceptual hydraulic design of the new water saving basin systems, features layout and design including the hydraulic, sensitivity, and probabilistic analyses, and the determination of preliminary mechanical and electrical issues related to valving operations. INCA was responsible for the conceptual structural design of the new water saving basin systems for Options 1 & 4, features layout and design (as related to structural issues for Options 1 & 4), and the development of drawings and input into the project report.

II. DATA COLLECTION

Please see the previously submitted report entitled, **"Final Report - Conceptual Design Study of Locks Water Saving Basins for Proposed Post-Panamax Locks at the Panama Canal"**. The noted report contains a detailed discussion of the data collection effort used for both the previous study and the current one in Chapter II.

III. DEVELOPMENT OF DESIGN CRITERIA

A. Need for Design Criteria

As stated before, this project is entirely unique in size and scope. Therefore, the design criteria need to be defined with care. The finalized criteria for each discipline (hydraulic, structural, geotechnical, mechanical, and electrical) follow. Due to the nature and scope of the project, the criteria are general in nature. However, the basic design items are detailed enough to provide proper guidance and direction in the preliminary design of the water saving basins to determine the feasibility of construction and their general operation.

B. Hydraulic Design Criteria

1. Properties of Water

Following is a list of the properties assumed:

Temperature: 24°C / 75.2°F

Based on information provided by ACP, fresh, brackish and fully saline water is found near the current locks. Based on recent measurements, the average salinities could be classified as follows:

Class	Salinity	Locations
Fresh	0 ppt	Gatun Lake, Upper Chamber at Gatun, Pedro Miguel Lock
Lower Brackish	1 ppt	Miraflores Lake, Middle Chamber at Gatun
Low Brackish	4.5 ppt	Lower Chamber at Gatun
Brackish	10 ppt	Downstream (D/S) of Gatun Locks During Emptying
High Brackish	20 ppt	Upper Chamber at Miraflores
Higher Brackish	26 ppt	Lower Chamber at Miraflores (D/S of Miraflores) During Emptying
Salt	33 ppt	Saline D/S at Gatun and Miraflores

These classes then have the following water properties:

Density (fresh):	997.3 kg/m^3 / 1.93 slugs/ft^3
Density (lower brackish):	998.1 kg/m^3 / 1.94 slugs/ft^3
Density (low brackish):	1000.7 kg/m^3 / 1.94 slugs/ft^3
Density (brackish):	1004.9 kg/m^3 / 1.95 slugs/ft^3
Density (high brackish):	1012.7 kg/m^3 / 1.96 slugs/ft^3
Density (higher brackish):	1017.4 kg/m^3 / 1.97 slugs/ft^3
Density (salt):	1022.9 kg/m^3 / 1.98 slugs/ft^3

Specific Weight (fresh):	9783.5 N/m^3 / 62.3 lb/ft^3
Specific Weight (lower brackish):	9790.9 N/m^3 / 62.3 lb/ft^3
Specific Weight (low brackish):	9817.1 N/m^3 / 62.5 lb/ft^3
Specific Weight (brackish):	9858.4 N/m^3 / 62.7 lb/ft^3

Specific Weight (high brackish):	9980.4 N/m^3 / 63.5 lb/ft^3
Specific Weight (salt):	10034.5 N/m^3 / 63.9 lb/ft^3
Dynamic Viscosity (fresh):	9.16 x 10-4 N∗sec/m^2 / 1.91 x 10-5 lb∗sec/ft^2
Dynamic Viscosity (lower brackish):	9.18 x 10-4 N∗sec/m^2 / 1.92 x 10-5 lb∗sec/ft^2
Dynamic Viscosity (low brackish):	9.26 x 10-4 N∗sec/m^2 / 1.93 x 10-5 lb∗sec/ft^2
Dynamic Viscosity (brackish):	9.39 x 10-4 N∗sec/m^2 / 1.96 x 10-5 lb∗sec/ft^2
Dynamic Viscosity (high brackish):	9.62 x 10-4 N∗sec/m^2 / 2.01 x 10-5 lb∗sec/ft^2
Dynamic Viscosity (higher brackish):	9.76 x 10-4 N∗sec/m^2 / 2.04 x 10-5 lb∗sec/ft^2
Dynamic Viscosity (salt):	9.92 x 10-4 N∗sec/m^2 / 2.07 x 10-5 lb∗sec/ft^2
Kinematic Viscosity (fresh):	9.19 x 10-7 m^2/sec / 9.89 x 10-6 ft^2/sec
Kinematic Viscosity (lower brackish):	9.20 x 10-7 m^2/sec / 9.90 x 10-6 ft^2/sec
Kinematic Viscosity (low brackish):	9.26 x 10-7 m^2/sec / 9.96 x 10-6 ft^2/sec
Kinematic Viscosity (brackish):	9.34 x 10-7 m^2/sec / 10.06 x 10-6 ft^2/sec
Kinematic Viscosity (high brackish):	9.50 x 10-7 m^2/sec / 10.23 x 10-6 ft^2/sec
Kinematic Viscosity (higher brackish):	9.59 x 10-7 m^2/sec / 10.33 x 10-6 ft^2/sec
Kinematic Viscosity (salt):	9.70 x 10-7 m^2/sec / 10.45 x 10-5 ft^2/sec

2. Hydraulic Analyses

a) Geometry

Specific details, dimensions, and layouts of the lock filling/emptying systems are unknown at this stage. The analysis will assume that the water saving basin conduits will tap into the lock filling/emptying system at the lock wall. Based on ACP direction, the water saving basin conduit soffit elevation shall be assumed to be fifteen feet below the proposed lock floor elevations. This assumption is based on direction given to the Project Team by ACP during the kickoff meeting. The details of this connection will not be determined at this stage, however, it will be assumed that the conduits will have perpendicular connections to the lock F/E culverts (as was assumed in Work Order No. 1).

Turbulence of the exiting flows into the water saving basins is not a critical design issue. The design will provide a reasonably smooth geometry that could be expected to perform satisfactorily for both filling and emptying operations. Final performance will have to be verified in hydraulic model tests at a later design phase.

The entrance losses (when filling the basins) and exit losses (when emptying the basins) will depend on flow characteristics through the lock F/E system. As in Work Order No. 1, the lock F/E system is assumed to be a bottom longitudinal manifold system for these preliminary analyses. Therefore, the loss coefficients will be based upon those selected for the previous work order. These loss coefficients will govern flows between the ports in the lock floor and the connection to the water savings basins in the lock wall. Using “typical” loss coefficients at this conceptual stage is justified since most authorities agree that the short distances between loss-generating elements in a lock filling/ emptying system causes the flow, hence the losses, to never

fully develop between each transition element. Therefore, the calculated losses using the sum of individual loss coefficients should be greater than the actual losses in the prototype system and thereby, using "typical" values should be conservative.

b) Frictional Properties of Conduits

The roughness height for the conduit will be allowed to vary to determine the hydraulic behavior of the system when just completed as well as when the system has aged considerably. Therefore, the required conduit size shall be determined using a 3.0 mm roughness height (most conservative), and the expected conduit velocity shall be estimated using a 0.01 mm roughness height (most conservative). While the value of 3.0 mm may seem high, the pitting that is evident on the existing conduit wall warrants a high value.

Roughness Height for Concrete Conduits: 0.01 mm – 3.0 mm

c) Water Saving Basin Performance

The maximum lock filling/emptying rate for the new locks and water saving basins shall be no greater than 2.28 m/min (7.5 ft/min) based on safe ship handling procedures in the current locks.

Along with the design constraint of a maximum F/E rate of 2.28 m/min (7.5 ft/min), a target total F/E operation time for the new locks equal to the current locks will be used as a guideline (3 operations*(8-9 min/operation) = 24-27 min total operation time – including valve operations). Therefore, for a two-lift lock, the target total F/E operation time would be 12-13.5 min/lift while for a one-lift lock, the target total F/E operation time would be 24-27 min.

Valve opening/closing times shall be approximately one minute and shall be included in the basin and lock filling/emptying times listed above, i.e., the total time for lock filling/emptying per lift for a three-lift lock is nine minutes, including valve operations.

The water saving basins will be sized to accommodate volumes **for 457.2 m (1500') lockage lengths only**. Based on guidance from ACP, it is expected that the times that the lockage lengths vary from 457.2 m (1500") to either 426.7 m (1400') or 487.7 m (1600') will be so infrequent that they should not be designed for. Rather, it is envisioned that during these times, specialized operations will be completed to either makeup or spill water depending on the lockage length. The dimensions of the water saving basin conduits will also be sized based on a 457.2 m (1500') lockage length based on ACP direction. Therefore, the filling/emptying rates and times for a 487.7 m (1600') lockage will likely be lower and longer than for the design condition of 457.2 m (1500').

d) Valves

Control shall be provided by either vertical lift, reverse tainter, or tainter valves depending on the specific application. Based on the results from Work Order No. 1, reverse tainter valves will be used for the preliminary design of the lock F/E system, while vertical lift valves will be assumed for the water saving basin conduit systems. The possibility of using bifurcated valves will be

investigated to reduce the overall size of the valves. Bulkhead slots will be provided on both sides of the valve chamber to effect closure for maintenance.

Streamlined contractions/expansions on both sides of the valve chamber will not be investigated in detail at this level of study. Ultimately, this should be investigated to determine if valves smaller than the overall conduit dimensions are feasible. Since flow through the system will be in both directions, transition rates will be no more than 1:6.

Valve operating times shall be assumed to be approximately one minute (opening and closing) as the existing timings of one minute for the existing rising stem valves are a valuable benchmark in that they have provided acceptable performance for many years in a system that is closer to the future prototype than other available examples. Furthermore, these are among the shortest valve times in use at any major lock. Faster valve timings will raise safety concerns and will increase uncertainty about whether it will be possible to maintain tranquil conditions within the lock during each WSB-to-lock filling operation.

Excessive negative pressures shall be avoided below the valve for both partial and full opening conditions.

e) Water Levels and Datums

Gatun Lake water levels have been described by statistics obtained through daily measurements for the period of 1966 to 2000. Based on the results from the statistical analysis, the range of water levels in Gatun Lake accounted for in the design will be reduced from the maximum range of 26.83 m (88.0’) - 23.92 m (78.5’) to a smaller range of 26.67 m (87.5’) - 24.69 m (81.0’). A detailed explanation of the design procedures using this reduced range of Gatun Lake water levels can be found in the following sections.

Water level variations on the Pacific side have also been described by exceedance statistics governed by measured tide data at Diablo Heights and predicted tides at Balboa. Based on the results from the statistical analyses and dredged channel limitations, the range of Pacific tide elevations designed for will be reduced from the maximum range of +3.60 m (+11.8’) to -3.44 m (-11.3’) to a smaller range of +3.60 m (+11.8’) to -2.32 m (-7.6’). A detailed explanation of the design procedures using this reduced range of Pacific Ocean tide levels can be found in the following sections.

Water level variations on the Atlantic side have also been described by exceedance statistics governed by measured tide data at Coco Solo and predicted tides at Cristobal. Based on the results from the statistical analyses and the limited variability in the Atlantic tide elevations, the full range of Atlantic tide levels +0.56 m (+1.85’) to -0.38 m (-1.25’) will be accounted for in the design. A detailed explanation of the design procedures using this range of Atlantic Ocean tide levels can be found in the following section.

All elevations reported and used for this project shall be referenced to P.L.D. (Precise Level Datum). The conversions of tidal datums to P.L.D. shall be as follows:

Table III.1 – Project Tidal Datums

Tidal Datum	Elevation (P.L.D.)	
	Pacific side	Atlantic side
Extreme High Water	+3.60 m (+11.8 ft)	+0.56 m (+1.85 ft)
Mean Sea Level	+0.304 m (+1.0 ft)	+0.06 m (+0.204 ft)
Mean Low Water	-2.32 m (-7.6 ft)	-0.12 m (-0.384 ft)
Extreme Low Water	-3.44 m (-11.3 ft)	-0.38 m (-1.25 ft)

f) Lockage Length

Based on guidance provided by ACP, the most common lockage length used for the new locks would be 457.2 m (1500'). Therefore, for the conceptual design of new locks' water saving basins, the lock dimensions were set to 457.2 m (1500') long by 61 m (200') wide.

g) Analysis Procedures

Based on the basin dimensions and required basin wall heights calculated during Work Order No. 1, ACP deemed it necessary to develop a specialized hydraulic analysis procedure to lower required lock and basin wall heights. For Work Order No. 1, the basin dimensions and wall heights were based upon designing them to account for **all** variability in water levels (lake and tide) and lockage lengths. It was felt that the resulting wall heights were quite high, and that a study to reduce expected wall heights and hence construction costs should be completed. Therefore, the following detailed procedures were developed for the conceptual design of the locks' WSBs to be completed during this work order.

With the exception of Option 4, the single-lift stacked basin arrangement, the same general design principles will be followed in this work order as in Work Order No. 1 concerning how the lift and step heights for each lock will be calculated. The design principles used for Option 4 will differ, however, since the m-factor (ratio of basin area to lock area), will be allowed to vary. The m-factor will be allowed to vary to eliminate necessary overlap between the stacked basins arranged on both sides of the lock. The general design principles and the hydraulic analysis procedures to be used for Options 1-3 and Option 4 are described separately below.

(1) General Hydraulic Design Principles Used for Options 1-3

As in Work Order No 1, for each multi-lift, side-by-side WSBs option, the total lift height (Lake Elev. – Tide Elev.) will be distributed among the number of lifts (locks). Since only one lockage length will be considered during this work order, this calculation is simplified further by just dividing the total lift height by the number of lifts (locks) for each option (lift heights will be equally distributed among number of lifts (locks)). For example, if the design lake level is 24.69 m (81.0') and the tide level (Pacific) is –2.32 m (-7.6'), the total lift height is 27.01 m (88.6'). For a two-lift (lock) option, the lift height per lift (lock) would therefore be 27.01 m /2 = 13.50 m (44.3').

The step heights for the water saving basins for each lift (lock) will also calculated similarly to procedures developed during the previous work order. Remember, for Options 1-3, the basin area is assumed to be equal to the lock area (m=1), so the number of basins (n) for a given water savings percentage can be calculated by:

$$\text{Water Savings Percentage} = \frac{n}{(n+2)}$$

Once the number of basins is known, the "step height" as shown in **Figure III.1** can be calculated. Knowing the number of basins for each option and that m=1, the total lift height would have to be divided into n+2 (n = number of basins) equal "step heights" for the entire system to work by gravity flow alone. Given the step heights, the starting and equalizing elevation for each operation can then be calculated by subtracting the step height from the lake elevation as the first equalization elevation. Subtracting the step height again would give the starting water surface elevation in the first basin as well as the equalization level of the second water saving basin. The process could continue for each basin and for each lock to determine the operating elevations for a given combination of lake and ocean levels.

For example, for our three-lift (lock) option with three water saving basins the cross-section for the upper (lakeside) lock would appear as seen in **Figure III.1**.

Again, the step height can be calculated by $= \dfrac{LIFT}{(n+2)}$ n = # of WSB,

then for WSB1, Equalizing ELEV = Lake Elev – Step Height
Starting ELEV = Equalizing Elev – Step Height,

etc., etc.

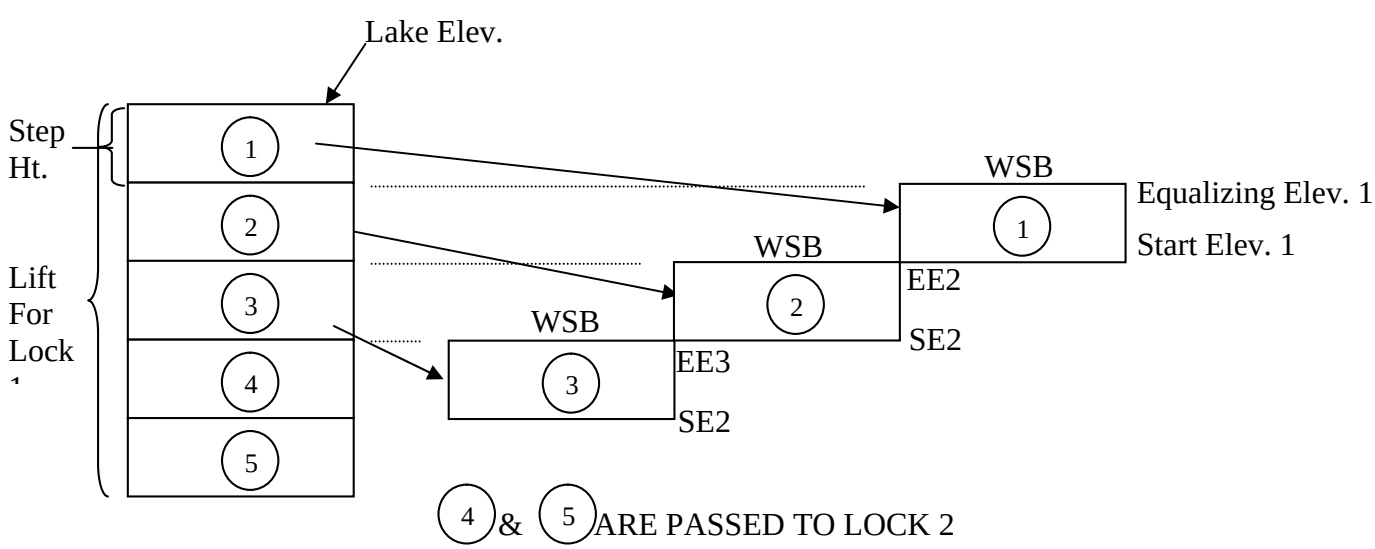


Figure III.1 – Conceptual Section Showing Calculation of WSB Operating Elevations

In using this procedure, the calculated lift heights provide the operational water levels in the locks, while the calculated step heights provide the operational water levels in the water saving basins. Again, the procedures outlined will provide the framework for the conceptual design of the new alternatives designed for a smaller range of operating conditions (water levels and only one lockage length).

(2) General Hydraulic Design Principles Used for Option 4

As stated before, the design procedure used for Option 4 (single-lift, stacked WSBs) will incorporate the m-factor such that the ratio of the basin area to lock area will vary for different lake and tide level scenarios so that required overlap between adjacent basins can be minimized if not eliminated. The calculated lift heights and step heights will be used to set the operational water levels in the locks and water saving basins, however, the calculations will differ slightly since the m-factor will almost certainly be greater than 1.

At this point it may be helpful to review the causes for the overlap between basins. The explanation below was taken from the previously submitted report entitled, **"Final Report - Conceptual Design Study of Locks Water Saving Basins for Proposed Post-Panamax Locks at the Panama Canal"**. This report considered varying lockage lengths as well, but the explanation is still applicable to the current project. The only change would be that the overlap would be reduced.

To better understand the concept of the "overlap", it would help to look at an example. For instance, for the upper lock of the two-lift lock system, the basin elevations required to provide the full theoretical water savings percentage for all combinations of water levels and lockage lengths are as shown in **Figure III.2**. The reason that this occurs can be traced back to the design procedures outlined on pages 13-14. With the wide variation in water levels and locakge lengths, there will also be variations in the lift heights calculated. Since these lift heights set the operational levels in the lock and its basins (see **Figure III.1**), there is a resulting variation in the operational elevations for the lock and basins. Completing these calculations for the entire range of design water levels and lockage lengths then gives us the range of operational elevations for each basin and the resulting overlap between adjacent basins as is illustrated below. This also illustrates why the considerable overlap required cannot be easily incorporated into a stacked basin arrangement. However, since the equalization process consists of equalizing volumes of water, the required overlap can be reduced by increasing the surface area of the basin in relation to the lock surface area (i.e., allowing the m-factor to be greater than 1).

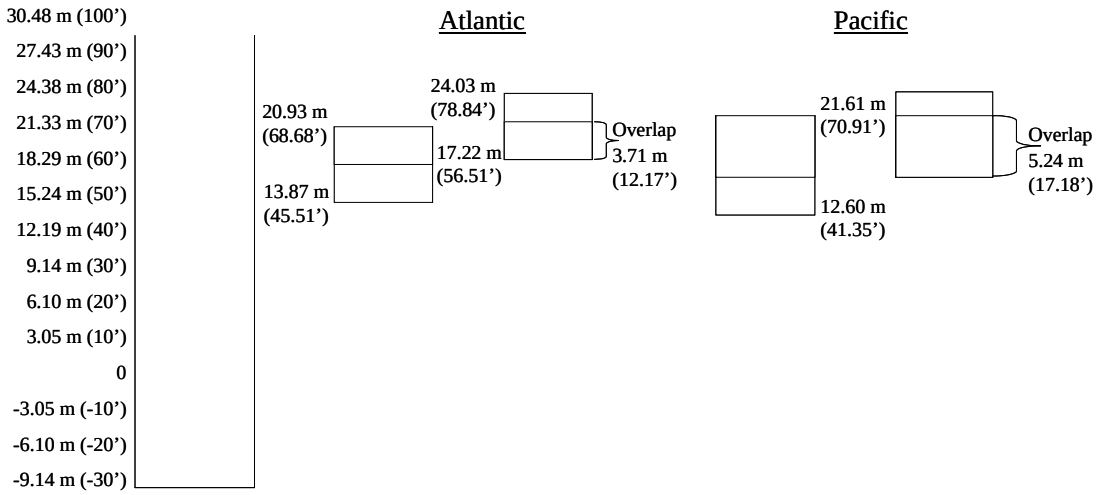


Figure III.2 – Overlap Requirements for Atlantic and Pacific Lakeside Locks (Metric and English Units Shown)

Since Option 4 incorporates a single-lift configuration, the lift height is equal to the difference in the lake level and tide level considered. Using the PIANC literature (see Figure III.3), the following equations were derived to compute the step height when $m \neq 1$:

$H - nt = V = t + 2e + h$, where

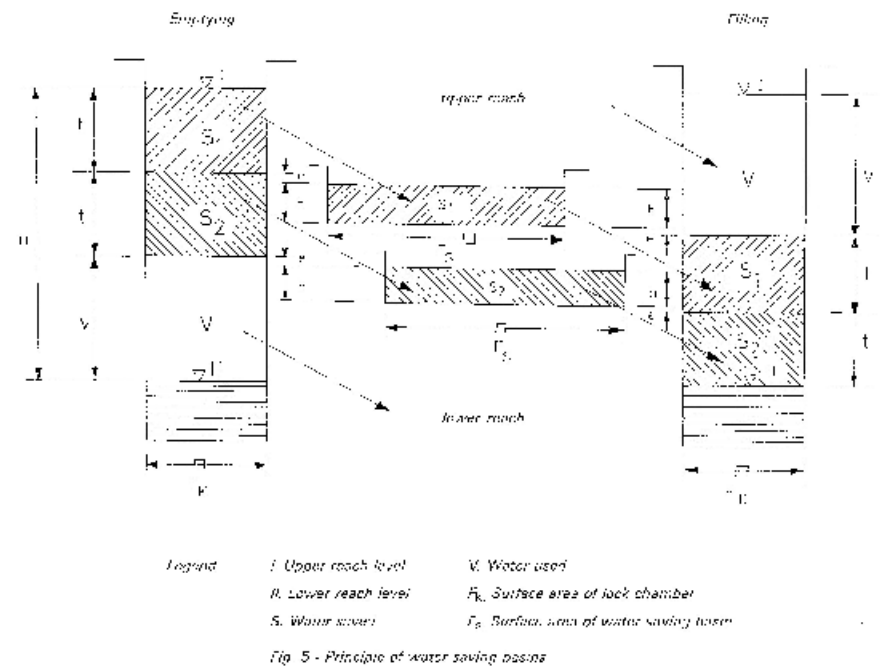
H = Lift
h = step height in basin
t = step height in lock
t = m*h

it can be shown that,

$$h = \frac{H - 2e}{(1 + m(1+n))}$$

Assume **H** >> 2e ("e" not set yet – should be optimized at a later design stage), then

$$h \cong \frac{H}{1 + m(1+n)} \qquad t = m*h$$



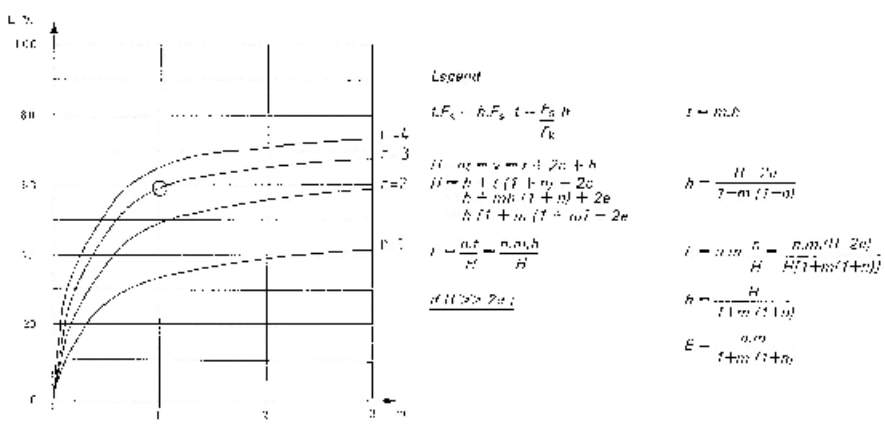


Figure III.3 – Figures Taken From PIANC Literature Describing WSB's

Given the above equations, h, the step height in the lock and t, the step height in the basin, can be computed and used to determine the equalization elevations for the lock and water saving basins as follows:

For WSB 1, Equalizing Elevation = Lake Elevation – t
Starting Elevation = Equalizing Elevation – h

For WSB 2, Equalizing Elevation = Equalizing Elevation WSB 1 – t
Starting Elevation = Equalizing Elevation WSB 2 – h

etc., etc…

These equations could then be placed in a spreadsheet, and the m-factor could then be varied until the required overlap between adjacent basins was eliminated so that the target water savings percentage could be reached. With the general hydraulic design procedures now set, the detailed hydraulic analysis procedures could be developed.

(3) Detailed Hydraulic Analysis Procedure

As stated previously, for this work order, the operating lockage length for all options studied will be fixed at 457.2 m (1500'). **Figure III.4** is intended to serve as an illustration of the applicable lake and tide elevations to be used in this analysis as well as the system features for which elevations will be defined. While **Figure III.4** illustrates Option 1, a 3-lift lock with 2 side-by-side water saving basins per lift, the following steps will be performed for all four proposed lock and basin alternatives.

The water saving basins' floor elevations and initial top of operating water surface elevations (TOWSEs) shall be set using the calculation procedures outlined above with a Gatun Lake elevation of 24.69 m (81.0') PLD and established low tide elevations for the Atlantic and Pacific Oceans of –0.38 m (-1.25') PLD (Extreme Low Water) and –2.32 m (–7.6') PLD (Mean Low Water Springs - MLWS) respectively. These calculated elevations provide the configuration setup discussed in the Description of Work provided by ACP. Due to the low variability of the tide on the Atlantic side, it was felt that the Extreme Low Water could be accounted for in the design of the Atlantic side options. However, given the fact that the approach channel limits larger ships to transit only when tides are above Mean Low Water Springs on the Pacific side, ACP staff felt that the lock and basin elevations should be designed to **fully** operate only at elevations above MLWS. The lake and ocean elevations used and the resulting fixed WSB floor elevations and top of operating water surface elevation for the lower lock determined by this step are shown on **Figure III.4** for Operation 1 (purple lines).

To allow for consistent and uninterrupted operation of the **locks**, the **lock** floor elevations shall be determined using the minimum lake level of 23.93 m (78.5') PLD and the low tide elevations for the Atlantic and Pacific Oceans, -0.38 m (-1.25') PLD and –2.32 m (–7.6') PLD, respectively. The lock floor elevations will be set 18.29 m (60') below the minimum water surface elevation in each lock (calculated using the procedures outlined on page 14) based on direction in the Description of Work. It is also assumed that the 0.61 m (2') sill clearance (that was included in Work Order No. 1) is not necessary for these analyses based on direction provided by ACP. The lake and tide elevations used and the lock floors for which elevations will be determined by this step are shown on **Figure III.4** for Operation 2 (green lines).

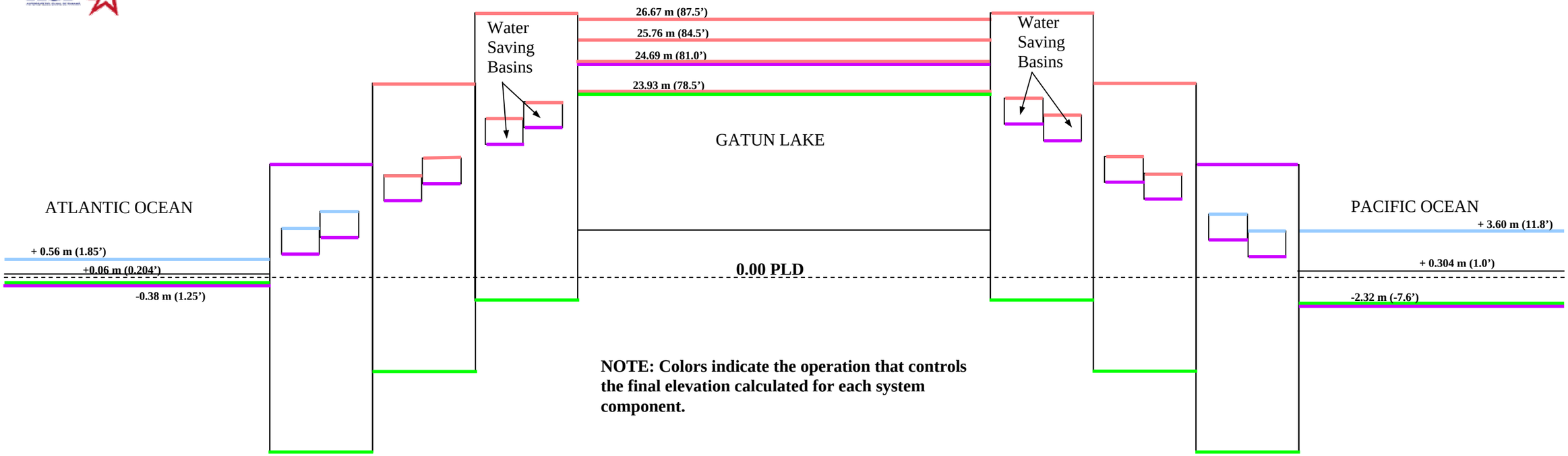
To minimize the influence of the tidal variability throughout the entire lock system, the lower lock top of the operating water surface elevation (TOWSE) and the WSB floor elevations for all locks shall be fixed using a Gatun Lake elevation of 24.69 m (81.0') PLD and the established low tide elevations for the Atlantic and Pacific oceans of –0.38 m (–1.25') PLD and –2.32 m (–7.6'), respectively (equivalent to the configuration setup arrangement discussed above and shown in **Figure III.4** for Operation 1 (purple lines)). Once these elevations have been fixed, separate groups of iterative calculations will be completed to determine: 1) the top of operating

water surface elevations (TOWSEs) for the upper and middle locks and their WSBs, and 2) the top of the operating water surface elevations (TOWSEs) for the lower lock WSBs (remember the lower lock top of operating water surface elevation is set using 24.69 m (81.0') and the established low tide elevation).

To calculate the **upper and middle (where applicable) locks'** and their WSB's top of operating water surface elevations (TOWSEs), an iterative process shall be performed to evaluate the impact of designing for higher and lower lake elevations in conjunction with the fixed lower lock top of operating water surface elevation described above, set in the configuration setup. This iterative process shall consist of completing multiple equalizations using various lake elevations [26.67 m (87.5'), 25.76 m (84.5'), 24.69 m (81.0'), 23.93 m (78.5')] along with the WSB floor elevations calculated in the configuration setup. The iterative calculations would also include complex checks to assure that the equalization elevations were not lower than the applicable basin floors. Since the first equalization is completed assuming the WSBs are empty, multiple sets of equalizations must be completed until the lock and WSB equalization elevations stabilize. Any water left in the lock above the fixed lower lock top of operating water surface elevation (TOWSE) is assumed to be spilled. Once the equalization levels of the upper and middle locks and their WSBs do stabilize, these elevations become the new TOWSEs for the upper and middle locks and their WSBs for a given lake elevation. The lake and fixed lower lock TOWSEs used and the lock and WSB TOWSEs determined by this step are shown on **Figure III.4** for Operation 3a (orange lines).

To calculate the lower lock WSB TOWSEs, another iterative process shall be performed. This process is simpler than the one described above as it will not vary with the different lake levels. This iterative process shall consist of completing multiple equalizations using the fixed lower lock TOWSEs set in the configuration setup along with the WSB floor elevations calculated in the configuration setup and the established high tide elevations [+0.56 m (1.85') – Atlantic, +3.6 m (11.8') – Pacific]. As a result, since the first equalization is completed assuming the WSBs are empty and the high tide will have an impact as the equalizations progress, a check must be made of the previous equalization elevation for the WSB against the established high tide elevation and the higher of the two chosen for the current equalization calculation. As with the upper and middle lock and WSB calculations, multiple sets of equalizations must be completed until the WSB equalization elevations stabilize. Once these equalization levels do stabilize, these elevations become the new TOWSEs for the lower lock WSBs. The lake and fixed lower lock TOWSEs used and the lock and WSB TOWSEs determined by this step are shown on **Figure III.4** for Operation 3b (blue lines).

Once the separate calculations for the upper, middle and lower locks have been completed, the results will be combined to form all possible elevation configurations for the system. Specifically, the single set of resulting elevations for the lower lock WSBs will be combined separately to the various sets of upper and middle locks' and their WSBs elevations (based on varying lake levels) to set all possible elevation configurations for the entire system.



ASSUMPTIONS

1. Only 457.2 m (1500') lockage lengths considered.

OPERATION	SYMBOL	GATUN LAKE ELEVATION	ATLANTIC OCEAN ELEVATION	PACIFIC OCEAN ELEVATION
1. Set WSB floor and initial top of operating water surface elevations (configuration setup) using the following lake and tide levels..		24.69 m (81.0')	-0.38 m (-1.25')	-2.32 m (-7.6')
2. Set lock chamber floor elevations using the following lake and tide levels.		23.93 m (78.5')	-0.38 m (-1.25')	-2.32 m (-7.6')
3. Iterative Process: a) Compute upper and middle (3-lift options) lock and WSB top of operating water surface elevations by completing multiple equalizations using the following combinations of lake and fixed lower lock top of operating water surface elevations set by operation 1 (multiple equalizations are completed for each condition until top of operating water surface elevations stabilize).		26.67 m, 25.76 m, 24.69 m, 23.93 m (87.5', 84.5', 81.0', 78.5')	Fixed Lower Lock Top of Operating Water Surface Elevations 3-Lift: 7.98 m (26.17') 2-Lift: 12.16 m (39.88')	Fixed Lower Lock Top of Operating Water Surface Elevations 3-Lift: 6.68 m (21.93') 2-Lift: 11.19 m (36.70')
b) Compute lower lock WSB top of operating water surface elevations by completing multiple equalizations using the fixed lower lock top of operating water surface elevations from operation 1 and the following tide levels (multiple equalizations are completed until top of operating water surface elevations stabilize).			+ 0.56 m (1.85')	+3.60 m (11.8')
Create curves of: (1) water used, (2) % water saved, (3) makeup water required, and (4) water spilled for all following combinations of lake and tide levels for each set of lock and WSB elevations set in operations 3a and 3b.		26.67 m, 25.76 m, 24.69 m, 23.93 m (87.5, 84.5, 81.5, 78.5)	+0.56 m, +0.06 m, -0.38 m (1.85', 0.204', -1.25')	+3.60 m, +0.304 m, -2.32 m (11.8', 1.0', -7.6')

Figure III.4 – Schematic Showing Hydraulic Analyses Procedures For All Options

For each of these elevation arrangements, calculations will then be made of water used, % water saved, water spilled, and make-up water required for all combinations of lake water levels [26.67 m (87.5'), 25.76 m (84.5'), 24.69 m (81.0'), and 23.93 m (78.5')] and tide levels [Atlantic - +0.56 m (1.85'), +0.06 m (0.204'), -0.38 m (-1.25'), Pacific - +3.60 m (11.8'), +0.304 m (1.0'), -2.32 m (-7.6')]. Parametric curves will be created using the results from these calculations to help ACP determine an optimized solution for the four options.

Additional steps, built upon the above procedures, will be performed with the hydraulic analysis, to study some more realistic operational impacts. The first step will involve the addition of uplockages and resets between the downlockages to determine the impacts on water usage and savings, for a range of events. This step will be performed for all of the lake and tide level combinations considered for Operation 3 and will involve the same iterative analyses described above. The final step will include limited functionality to study the impacts of the varying tide elevation on the system. The analysis will also allow adjustment of the tide elevation for each iteration based on a calculated rate of change and will evaluate the impact of this change on water usage and savings, for the range of lake and tide level combinations. This analysis will also be performed for downlockages, uplockages, and resets as in the previous step.

(4) Modifications to Hydraulic Analysis Procedure for Option 4

To eliminate the occurrence of overlap between the stacked basins for Option 4 experienced on the Pacific Ocean side, the basins are assumed to be placed on both sides of the lock in an alternating fashion (i.e. 1A, 1C, and 1E on one side, 1B, 1D, and 1F on the other side – see **Figure III.5**). An additional height of 3 feet between the basins was also allotted for the basin thickness (1') and for freeboard (2') at the top of the basins. Therefore, in the resulting hydraulic analysis calculations, the equalizations between the basins and the lock were controlled so that the top of operating water surface elevation for any lower basin did not exceed an elevation 0.91 m (3') below the floor of the basin above it in order to minimize the probability of overfilling the basins.

The hydraulic analysis procedure for Option 4 followed the same general procedure described above, with some modifications resulting from the addition of the basin to lock surface area ratio (m) factor. The design procedure used for Option 4 incorporated the m-factor such that the ratio of the basin area to lock area varied for different lake and tide level scenarios. The lift heights for the lock and step heights for the basins and lock (h, t) were calculated as described in the hydraulic design criteria to set the operational water levels in the lock and water saving basins. In Operation 3a, and prior to beginning the iterative analysis described in the general hydraulic analysis procedure above, the m-factor was adjusted for the basic configuration until the theoretical water savings percentage was achieved. This basic configuration was then used through the remaining steps in the general procedure, as described above.

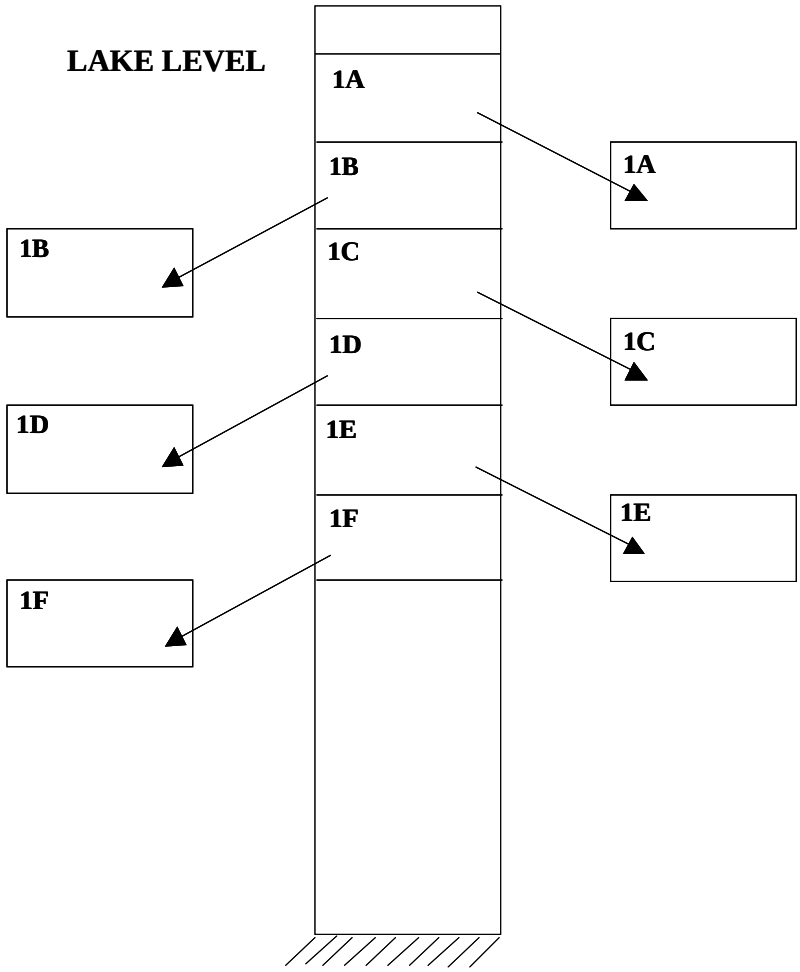
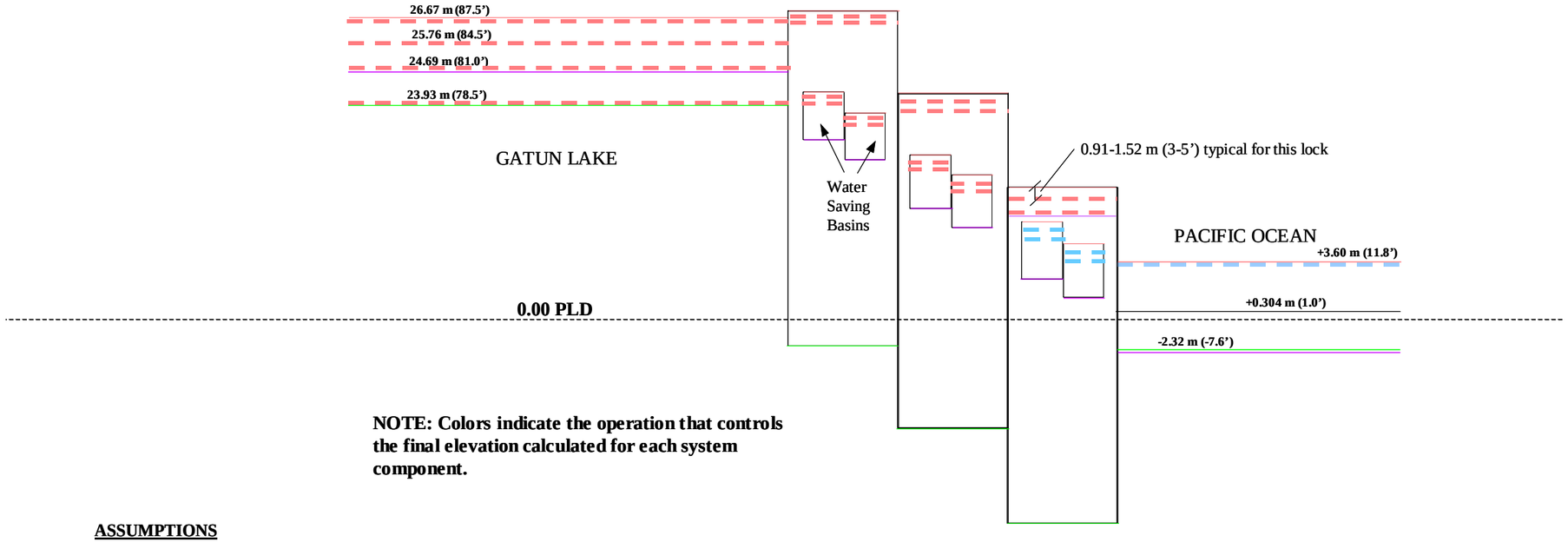


Figure III.5 – Schematic Showing Assumed Basin Operation Progression for Option 4 to Minimize Overlap

(5) Sensitivity Analysis Procedure

A sensitivity analysis (see **Figure III.6**) was also be performed for the multi-lift Pacific Ocean options to determine the effects of allowing the **lower lock and its WSB elevations** to be designed for a wider range of lake and tide elevations to minimize overall water usage and spillage. This will be done by first setting the lower lock and WSB top of operating water surface elevations (TOWSEs) using the procedures described on page 14 (theoretical levels will be calculated so no spilling occurs) with the high lake level [26.67 m (87.5')] and the high tide level [+3.60 m (11.8')] elevation. Once this is completed, alternative lock and WSB top of operating water surface elevation sets will be calculated by lowering the lower lock top of operating water surface elevation from the maximum described above (where no spilling occurs) by 0.91 m – 1.52 m (3'-5') increments until the elevation set by the combination of 24.69 m (81.0') (lake) and –2.32 m (–7.6') (tide) – (configuration setup – Operation 1) is reached.



NOTE: Colors indicate the operation that controls the final elevation calculated for each system component.

ASSUMPTIONS

1. Only 457.2 m (1500') lockage lengths considered.

OPERATION	SYMBOL	GATUN LAKE ELEVATION	PACIFIC OCEAN ELEVATION
1. Set WSB floor and initial top of operating water surface elevations (configuration setup) using the following lake and tide levels.		24.69 m (81.0')	-2.32 m (-7.6')
2. Set lock chamber floor elevations using the following lake and tide levels.		23.93 m (78.5')	-2.32 m (-7.6')
3. Set lock and WSB top of operating water surface elevations using the following lake and tide levels.		26.67 m (87.5')	+3.60 m (11.8')
4. Iterative Process: a) Compute upper and middle (3-lift options) lock and WSB top of operating water surface elevations by completing multiple equalizations after lowering the lower lock top of operating water surface elevation computed in operation 3 by 0.91-1.52 m (3-5') intervals until the following lower lock top of operating water surface elevations (set by operation 1) are reached (multiple equalizations are completed for each condition until top of operating water surface elevations stabilize).	Iterations	26.67 m, 25.76 m, 24.69 m, 23.93 m (87.5', 84.5', 81.0', 78.5')	Lowest Fixed Lower Lock Top of Operating Water Surface Elevations 3-Lift: 6.68 m (21.93') 2-Lift: 11.19 m (36.70')
b) Compute lower lock WSB top of operating water surface elevations by completing multiple equalizations using the fixed lower lock top of operating water surface elevations from operation 4a and the following tide level (multiple equalizations are completed until top of operating water surface elevations stabilize).	Iterations		+3.60 m (11.8')
Create curves of: (1) water used, (2) % water saved, (3) makeup water required, and (4) water spilled for all following combinations of lake and tide levels for each set of lock and WSB elevations set in operations 3 and 4a and 4b.		26.67 m, 25.76 m, 24.69 m, 23.93 m (87.5', 84.5', 81.0', 78.5')	3.60 m, 0.304 m –2.32 m, -3.44 m (11.8', 1.0', -7.6', -11.3')

Figure III.6 – Schematic Showing Sensitivity Analyses Procedures For Multi-Lift Pacific Side Options

As the lower lock top of operating water surface elevation is lowered in the 0.91 m – 1.52 m (3'-5') increments, separate sets of iterative calculations will again be required for 1) the upper and middle locks and their WSBs and 2) the lower lock WSBs. The procedures for these calculations will be identical to those discussed previously.

Also as before, once the separate calculations for the upper, middle and lower locks have been completed, the results will be combined to form all possible elevation configurations for the entire system. Specifically, the multiple sets of resulting elevations for the lower lock WSBs will be combined separately to the various sets of upper and middle locks' and their WSBs elevations (based on varying lake levels) to set these possible elevation configurations for the entire system.

Finally, for each of the resulting elevation sets, calculations will then be made of water used, % water saved, water spilled, and make-up water required for all combinations of lake water levels [26.67 m (87.5'), 25.76 m (84.5'), 24.69 m (81.0'), and 23.93 m (78.5')] and tide levels [+3.60 m (11.8'), +0.304 m (1.0'), -2.32 m (-7.6'), and –3.44 m (**-11.3**')]. Parametric curves will be created using the results from these calculations to help ACP determine an optimized solution for the three multi-lift Pacific options. **Figure III.6** shows the combinations of lake and tide levels used for Operations 3 (orange lines) and 4 (dashed orange and blue lines) used in this sensitivity analysis.

(6) Features Analyses and Layout

Once the optimized basin layouts and geometries (wall heights, etc.) have been selected and finalized by ACP, conduits sizes and arrangements shall be analyzed using standard closed conduit hydraulic procedures as outlined in EM 1110-2-1604, "Hydraulic Design of Navigation Locks", as was done for Work Order No. 1.

The analysis accounts for inertia head. The inertia head is defined as:

$$H_{\text{inertia}} = \frac{L}{g}\int\frac{dv}{dt}$$

For purposes of calculation, the differential is approximated by the change in velocity between consecutive time steps (normally one second). By including the inertia head term, the flow between the lock and basins will cause the water level in the receiving basin to "overtravel" or rise beyond the nominal equilibrium level represented by the arithmetic average of the initial water levels.

h) Loss Coefficients

Loss coefficients will be assigned to each feature of the conduit system using published values from standard texts, Corps EM's, USCOE's Hydraulic Design Criteria, and other published hydraulic texts and model test reports. Typical losses include:

- Entrance
- Gates/Valves

- Transitions
- Expansions/Contractions
- Bends
- Exit

Past experience has shown that the cumulative loss coefficients overstate the losses for the entire system taken as a whole. Therefore, the individual loss coefficients were adjusted, as needed, to yield overall loss coefficients that are in line with measured "norms" for similar systems obtained from hydraulic model tests.

Variable loss and discharge coefficients will be included in the analysis as a function of valve opening/closing percentages based on guidance within USCOE's Hydraulic Design Criteria.

Separate values for loss coefficients will be assigned at each location according to flow direction to account for preferred geometries that must necessarily exist for flow in either direction.

i) Cavitation and Air Demand

Cavitation and air demand shall not be examined in detail at the concept study level. Ultimately, pressures within the system should be analyzed to determine where air vents may be required. Pressure drops that occur immediately downstream of the valve slots should also be included in the analysis. Air will be provided if expected negative pressures below the valves may exceed –3.048 meters (-10 feet).

The need for steel liners just below the valves should be investigated based on exit velocities and pressures below the valves.

Air demand shall be provided with vents, if necessary, to offset negative pressures in the conduits that cannot be controlled by varying the conduit geometry.

j) Other Items

Conduit velocities will be checked to verify that scouring of the lining will not occur.

3. References

Fluid properties, design procedures, loss coefficients, etc. from the hydraulic publications listed in **Appendix A** will be used in the design of the water saving basins systems.

C. Structural Design Criteria

Please see the previously submitted report entitled, **"Final Report - Conceptual Design Study of Locks Water Saving Basins for Proposed Post-Panamax Locks at the Panama Canal"**. The noted report contains a detailed discussion of the structural design criteria used for both the previous study and the current one in Chapter III.C.

D. Geotechnical Design Criteria

Please see the previously submitted report entitled, **"Final Report - Conceptual Design Study of Locks Water Saving Basins for Proposed Post-Panamax Locks at the Panama Canal"**. The noted report contains a detailed discussion of the geotechnical design criteria used for both the previous study and the current one in Chapter III.D.

E. Mechanical Design Criteria

Please see the previously submitted report entitled, **"Final Report - Conceptual Design Study of Locks Water Saving Basins for Proposed Post-Panamax Locks at the Panama Canal"**. The noted report contains a detailed discussion of the mechanical design criteria used for both the previous study and the current one in Chapter III.E.

F. Electrical Design Criteria

Please see the previously submitted report entitled, **"Final Report - Conceptual Design Study of Locks Water Saving Basins for Proposed Post-Panamax Locks at the Panama Canal"**. The noted report contains a detailed discussion of the electrical design criteria used for both the previous study and the current one in Chapter III.F.

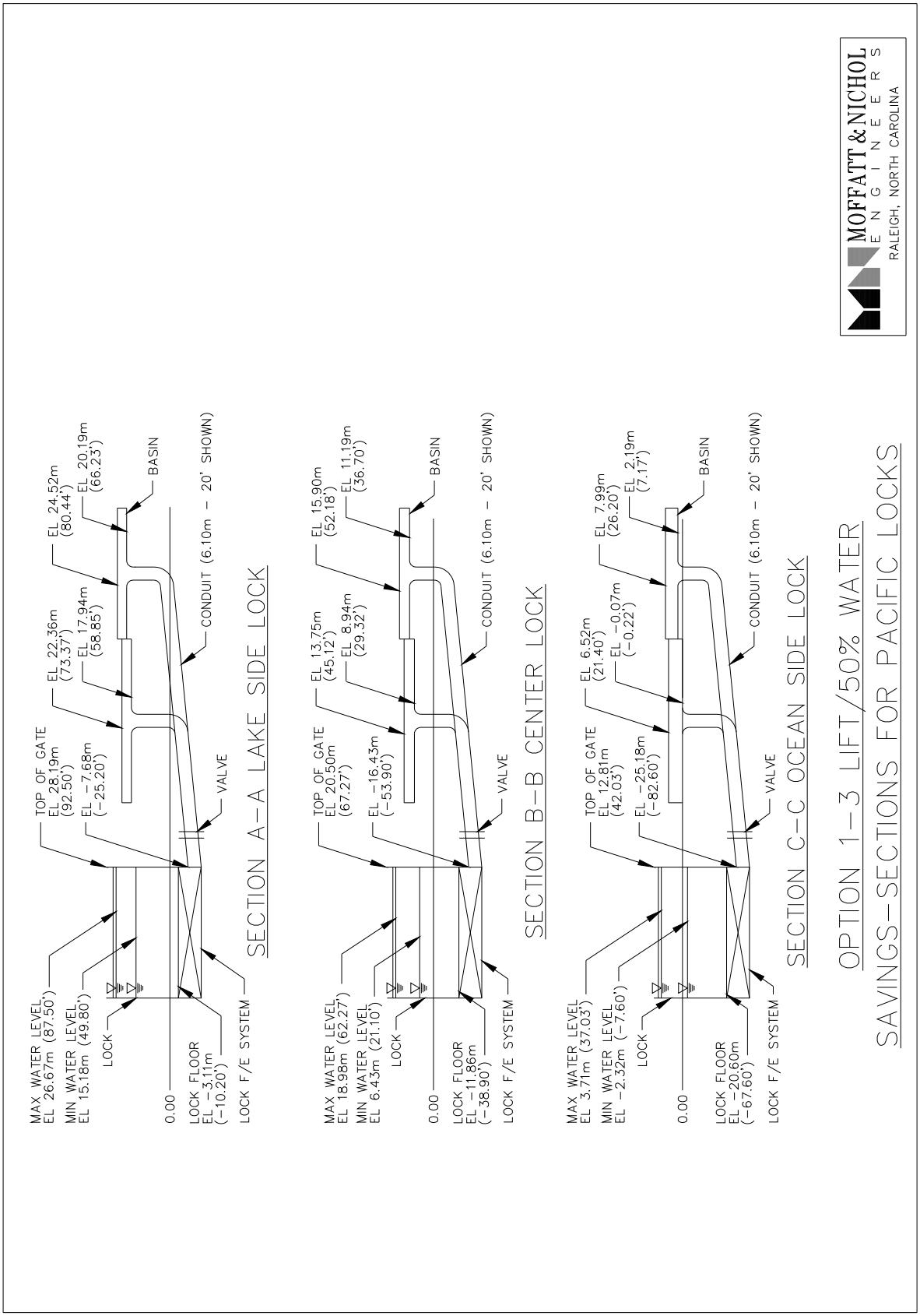


Figure IV.28 – Option 1 – Section View (Pacific Side)

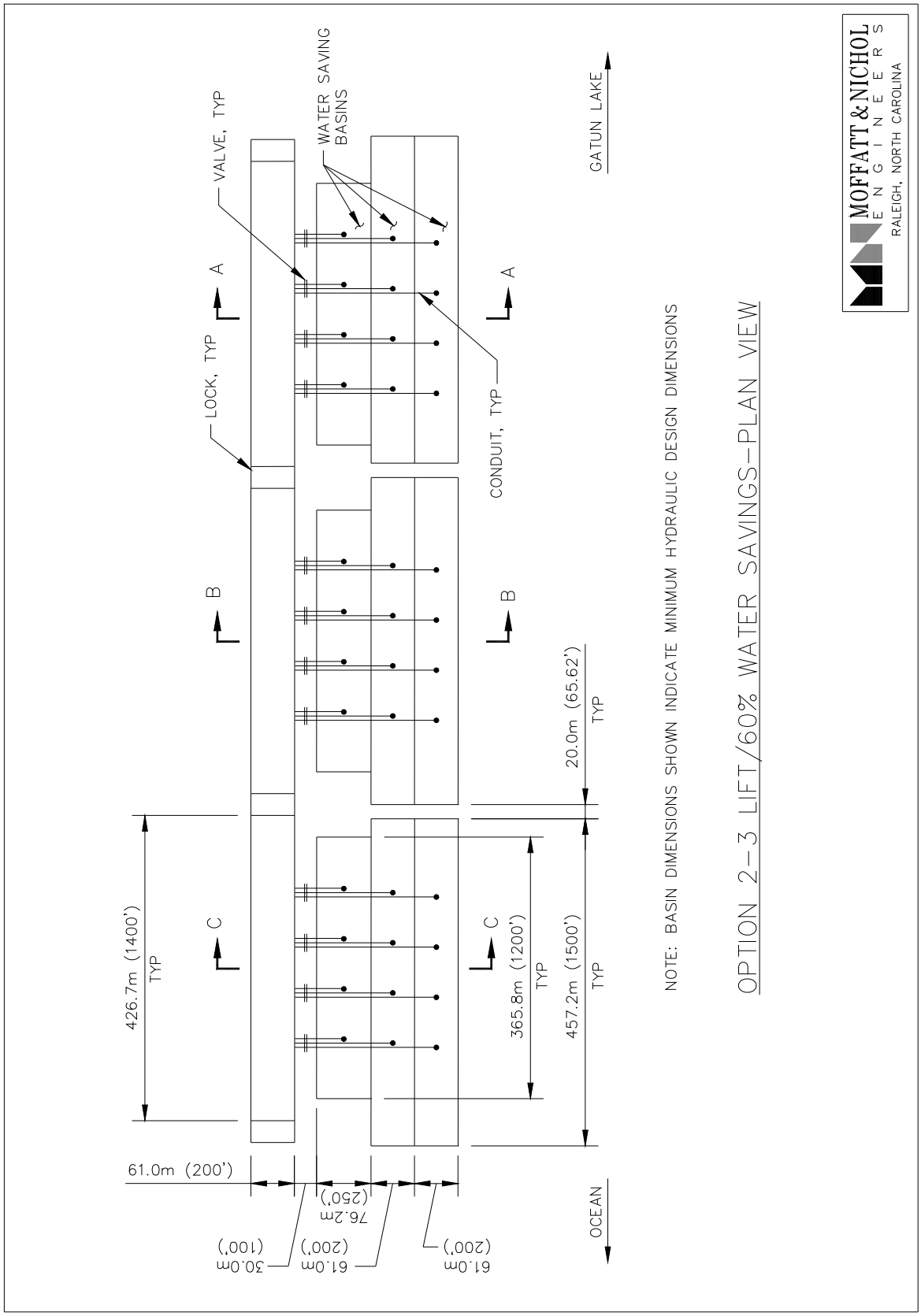


Figure IV.29 – Option 2 – Plan View

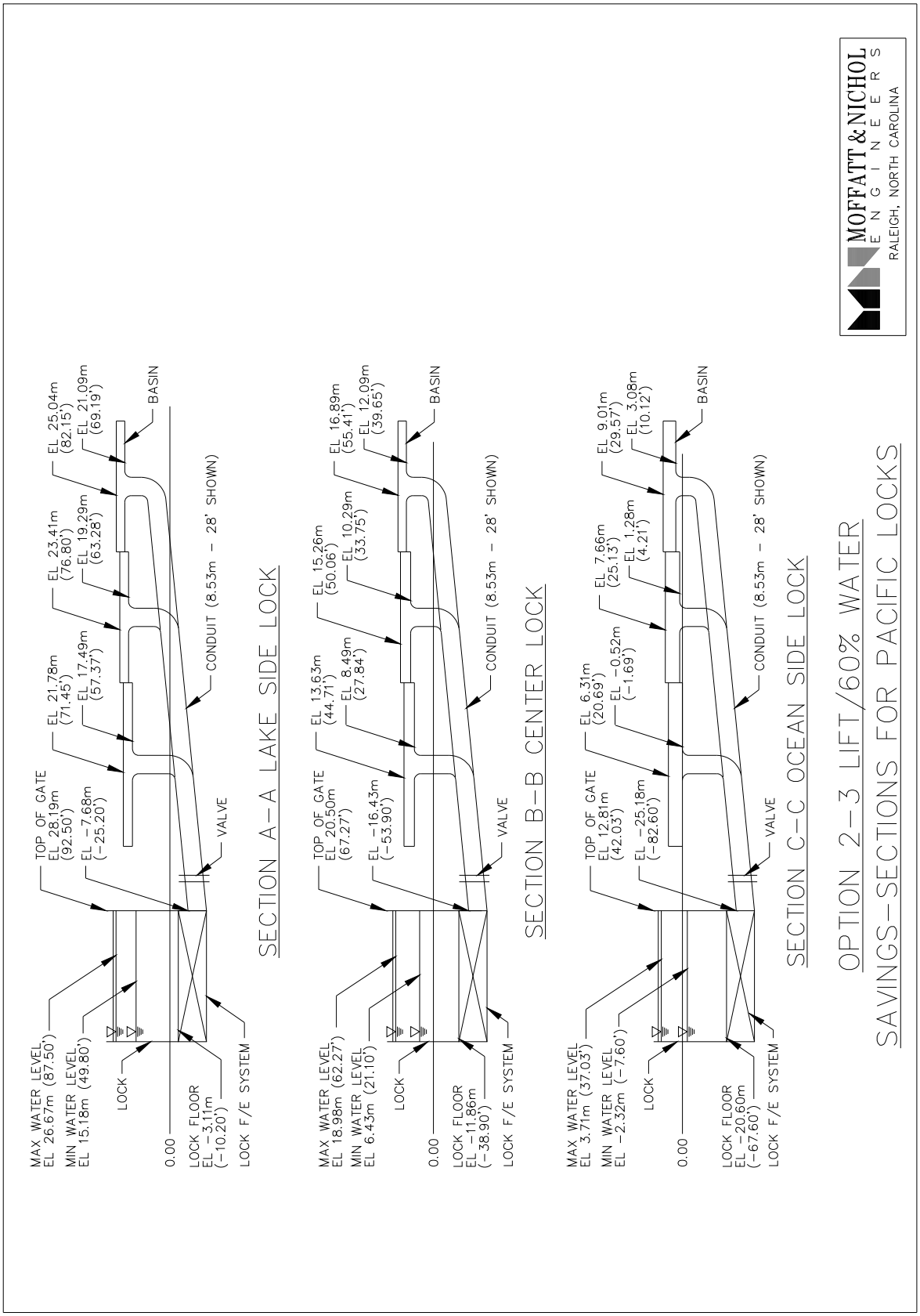


Figure IV.30 – Option 2 – Section View (Pacific Side)

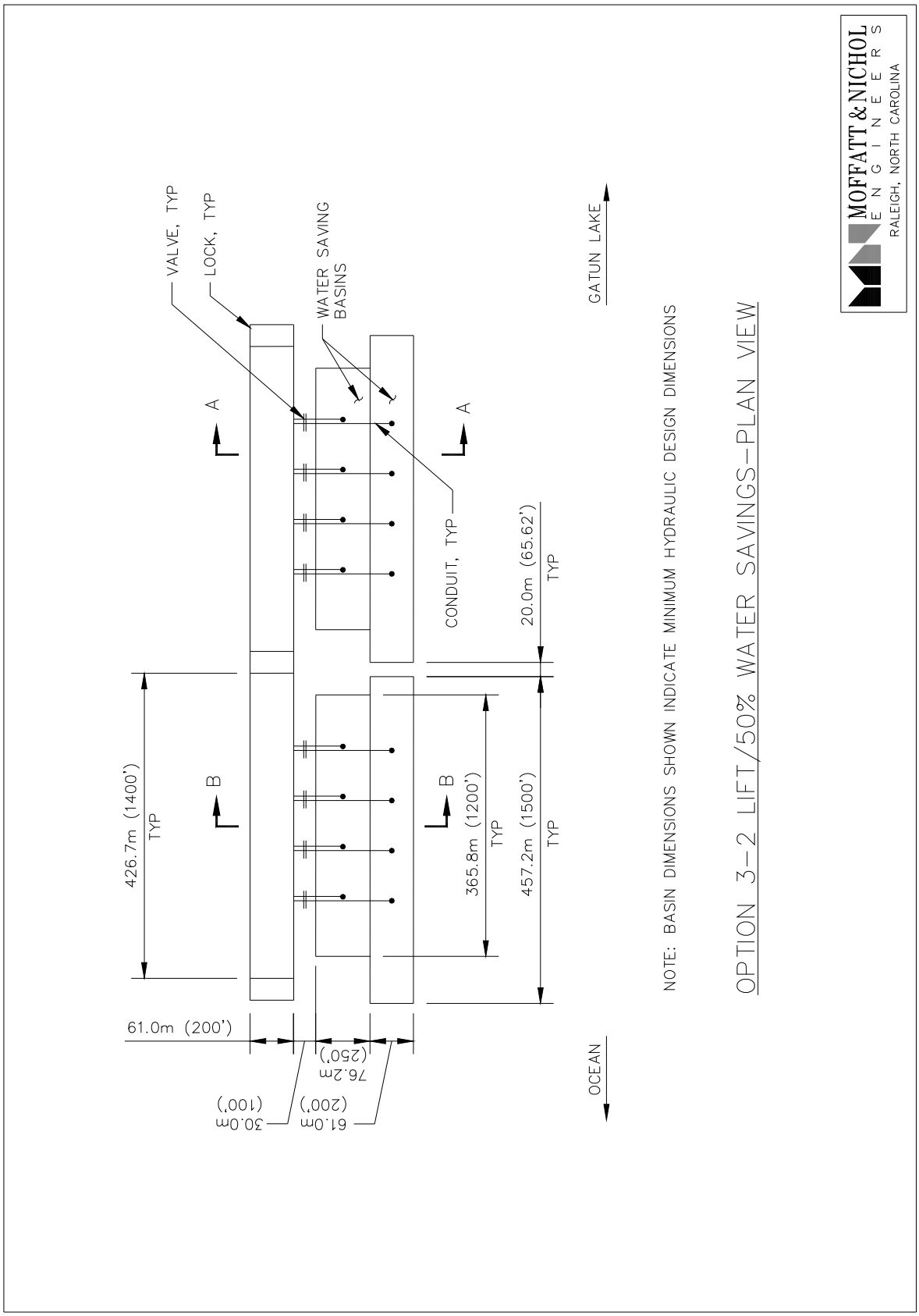


Figure IV.31 – Option 3 – Plan View

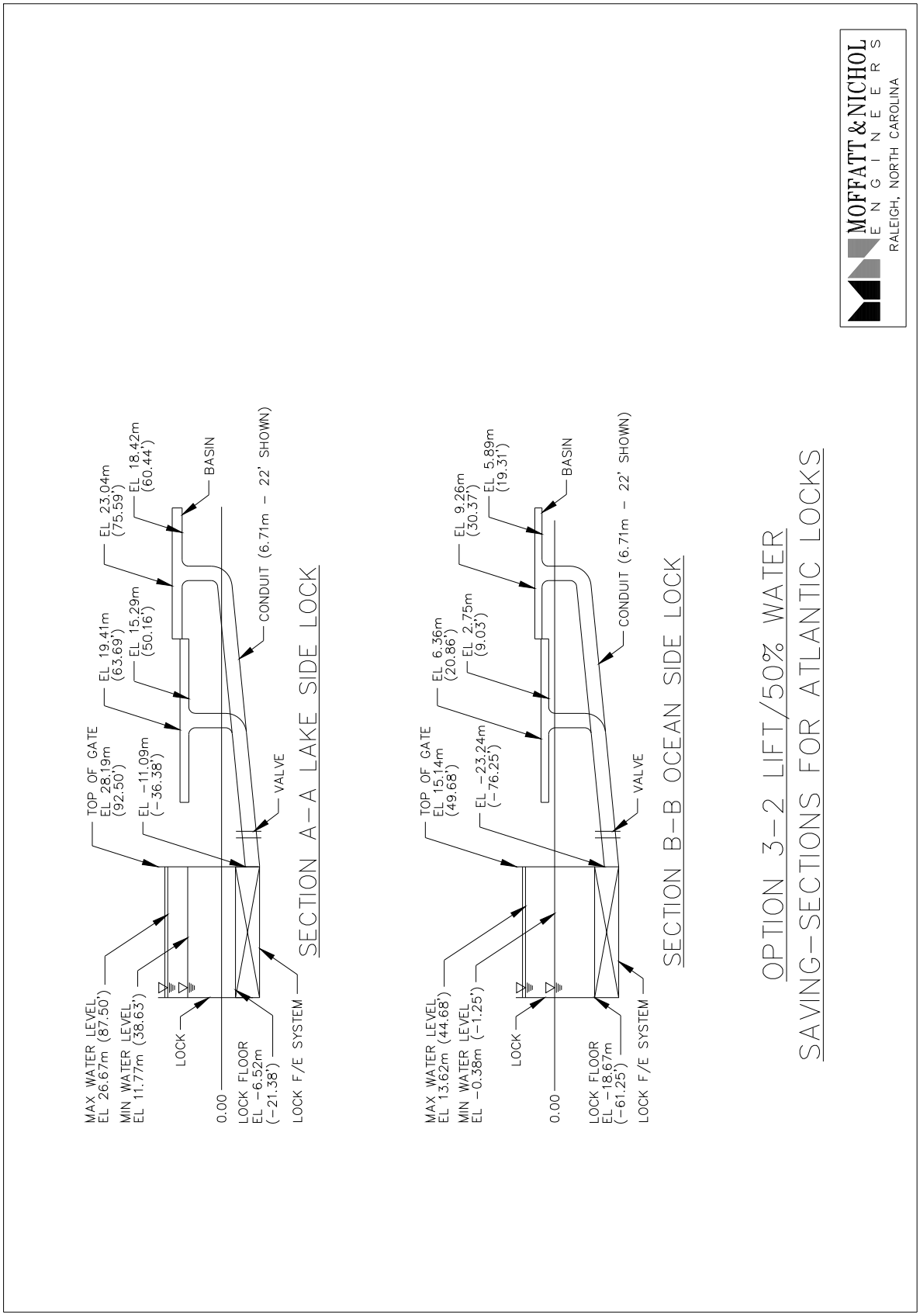


Figure IV.32 – Option 3 – Section View (Atlantic Side)

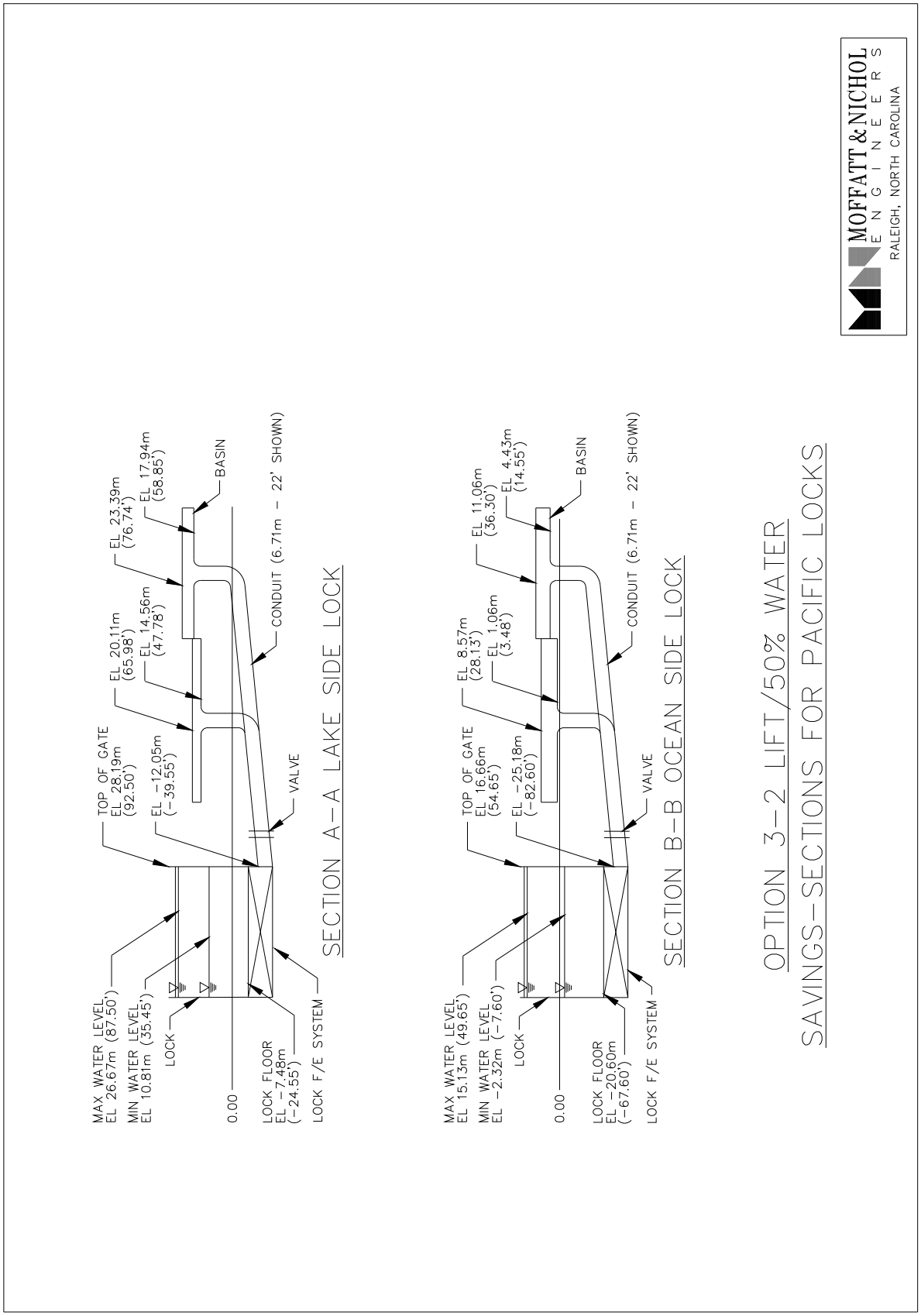


Figure IV.33 – Option 3 – Section View (Pacific Side)

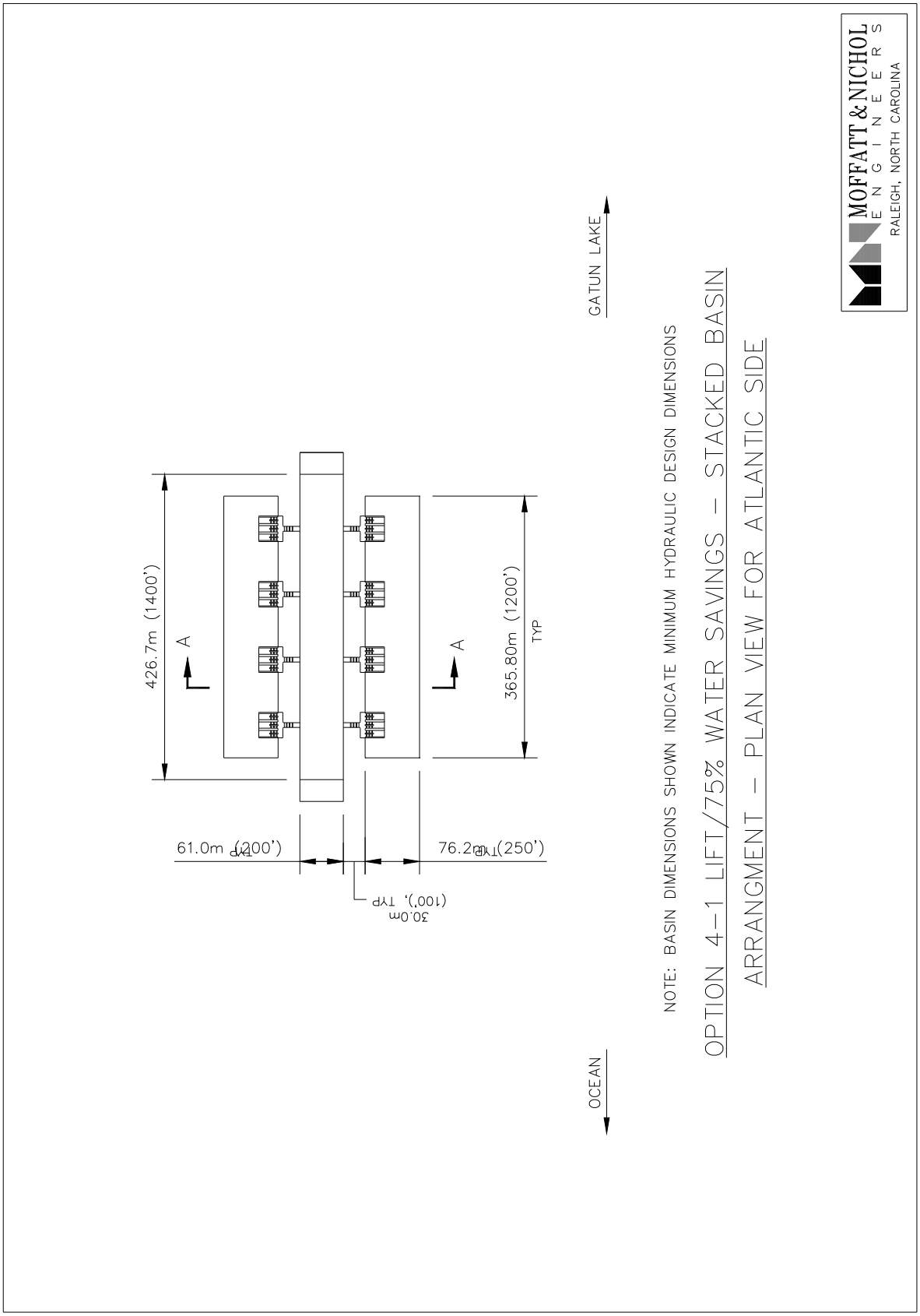


Figure IV.34 – Option 4 – Plan View – Atlantic Side

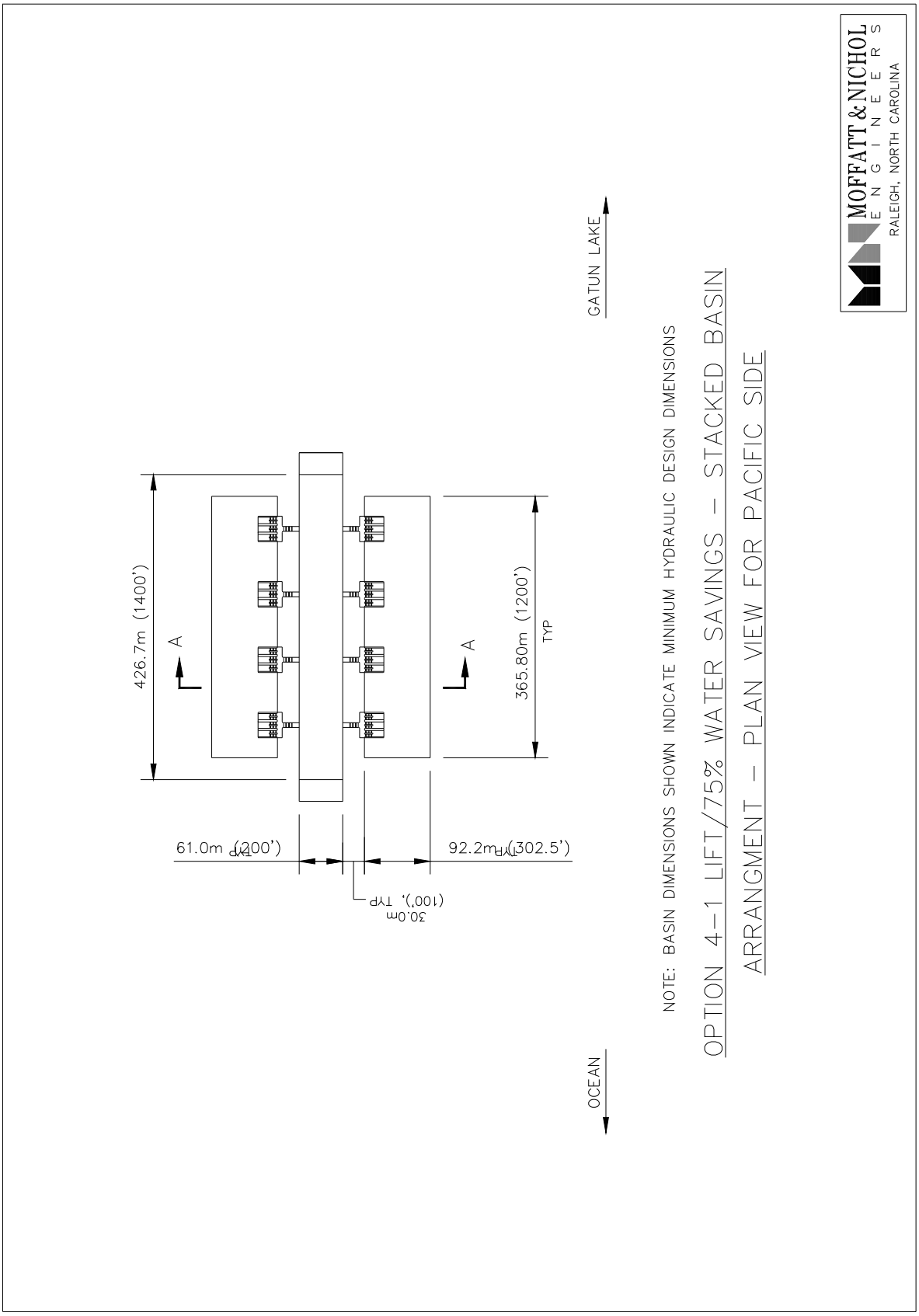


Figure IV.35 – Option 4 – Plan View – Pacific Side

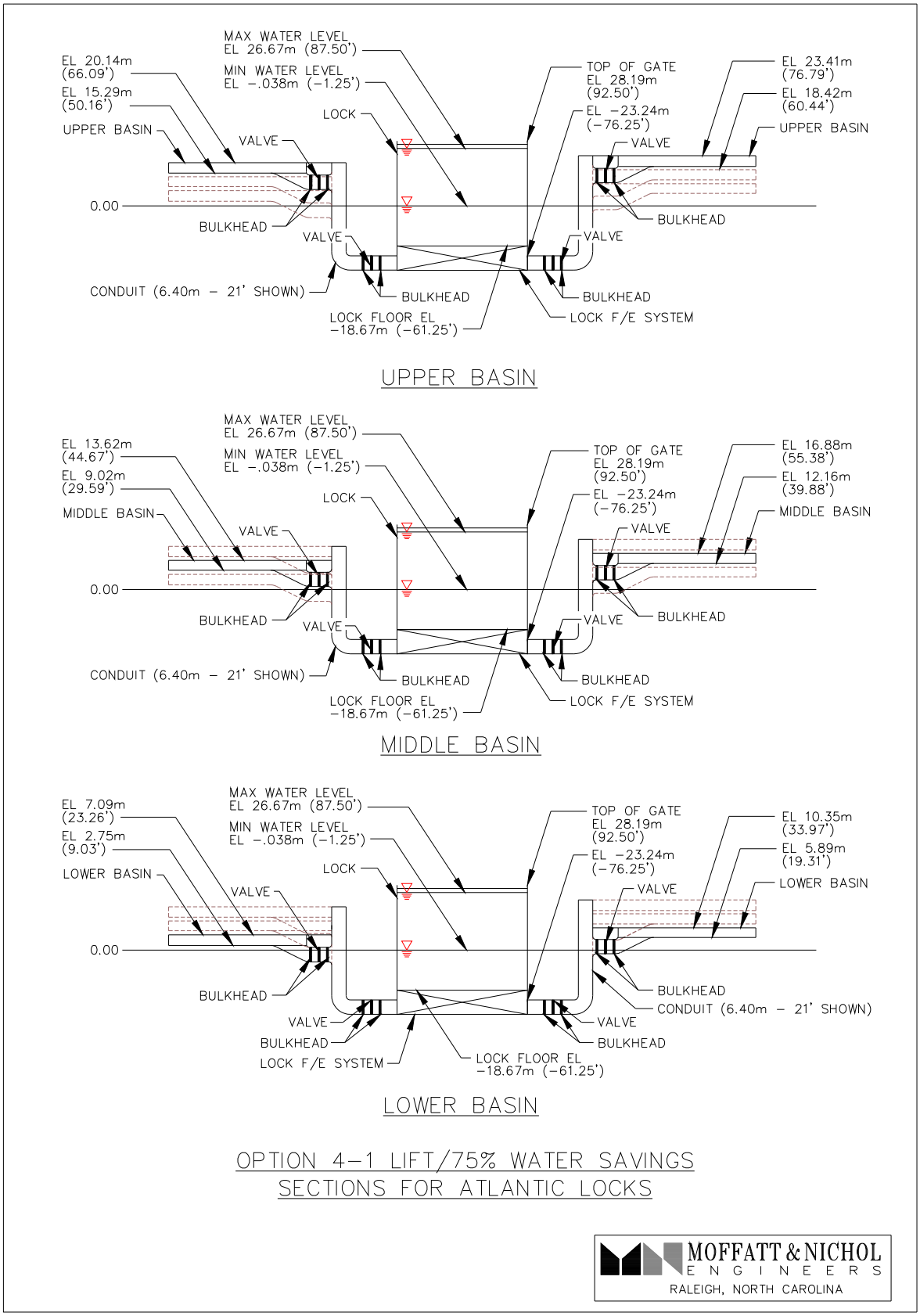


Figure IV.36 – Option 4 – Section View (Atlantic Side)

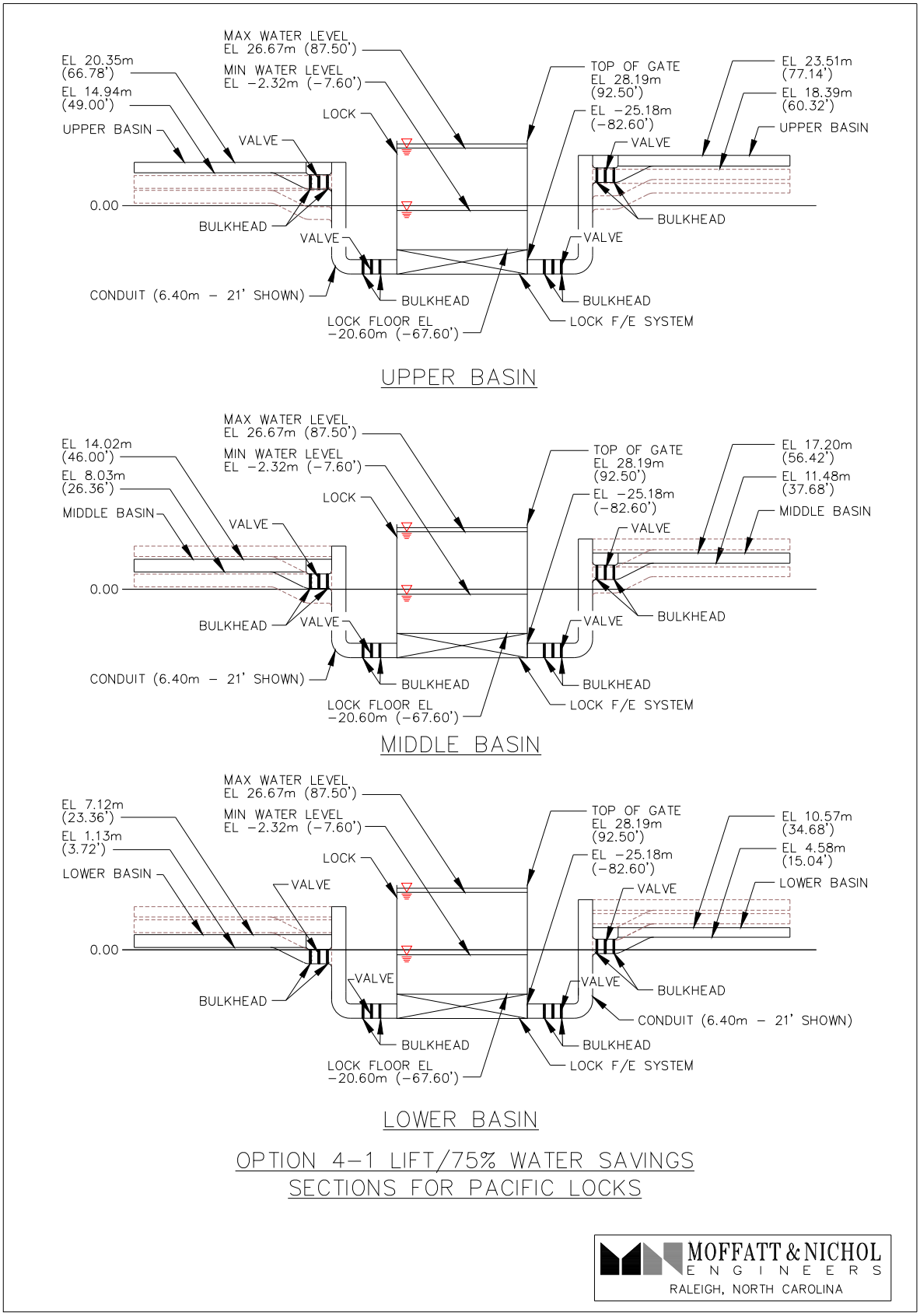


Figure IV.37 – Option 4 – Section View (Pacific Side)

i) Salinity Considerations

The impact of the salinity differential between the ocean and the lock water on equalization levels is another complicating factor that was not included at this conceptual stage but should be included in later design. This differential equalization level is due to the fact that the lock and ocean will not equalize to the same elevation since saline water is more dense than freshwater. Consequently, at the end of equalization, the water level in the lock may be higher than that in the ocean if there is a large salinity difference. After some preliminary calculations using the salinity data presented in **Chapter III**, and discussions with ACP staff, it was agreed that these effects could be incorporated at a later design phase since this phenomenon represents second or third order behavior when compared with tide differentials.

3. Structural/Civil Features Layout Design

a) Atlantic Side

(1) General

To limit excavation costs, the footprint of the new lock lanes and water saving basins was minimized. This was accomplished by placing the basins for each lift adjacent to each other and sizing basins to fit between the lock roller gate monoliths. To centralize operations, alignment A-2 was located as close as possible to the existing Gatun Locks. (*Conduits are not shown on the drawings as they were not sized prior to the termination of this work.*)

(a) Option 1 Configuration

The Option 1 configuration for the water saving basins is shown in **Figure IV.38**. Option 1 consists of six side-by-side basins for a three-lift lock, with two basins per lift. The lower basin for each lift is 365.8 m (1200 ft.) long by 76.2 m (250 ft.) wide. The upper basin for each lift is 457.2 m (1500 ft.) long by 61.0 m (200 ft.) wide.

(b) Option 2 Configuration

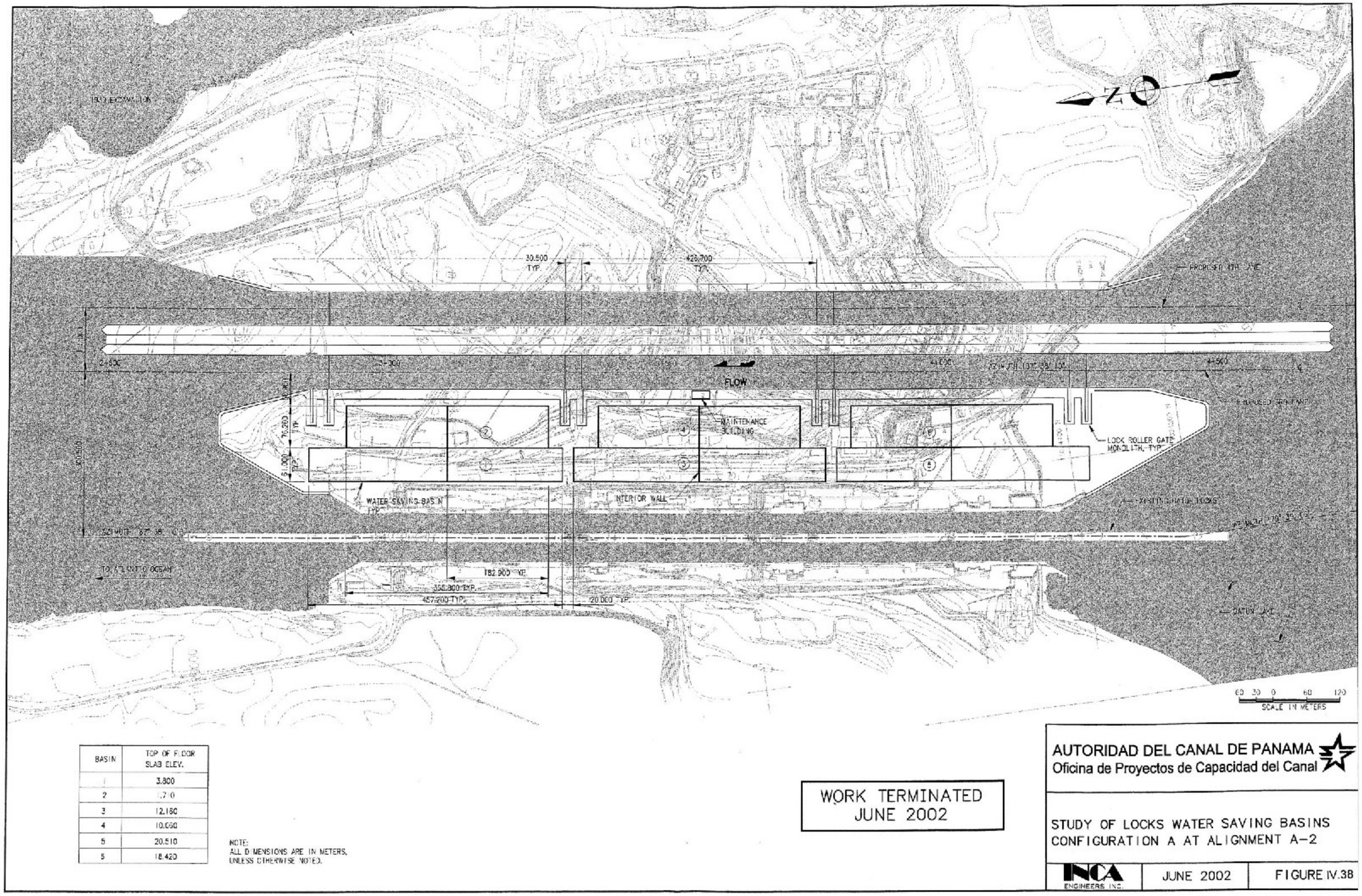
The Option 2 configuration for the water saving basins is shown in **Figure IV.39**. Option 2 consists of nine side-by-side basins for a three-lift lock, with three basins per lift. The lower basin for each lift is 365.8 m (1200 ft.) long by 76.2 m (250 ft.) wide. The middle and upper basins for each lift are 457.2 m (1500 ft.) long by 61.0 m (200 ft.) wide

(c) Option 3 Configuration

The Option 3 configuration for the water saving basins is shown in **Figure IV.40**. Option 3 consists of a total of four side-by-side basins for a two lift lock, with two basins per lift. The lower basin for each lift is 365.8 m (1200 ft.) long by 76.2 m (250 ft.) wide. The upper basin for each lift is 457.2 m (1500 ft.) long by 61.0 m (200 ft.) wide.

(d) Option 4 Configuration

(*The stacked basins required for Option 4 were not addressed as they were not sized prior to the termination of this work.*).



BASIN	TOP OF FLOOR SLAB ELEV.
1	3.800
2	[illegible]
3	12.180
4	10.090
5	20.510
6	18.420

Figure IV.38 – Option 1 Configuration (Structural Features Layout)– Atlantic Side

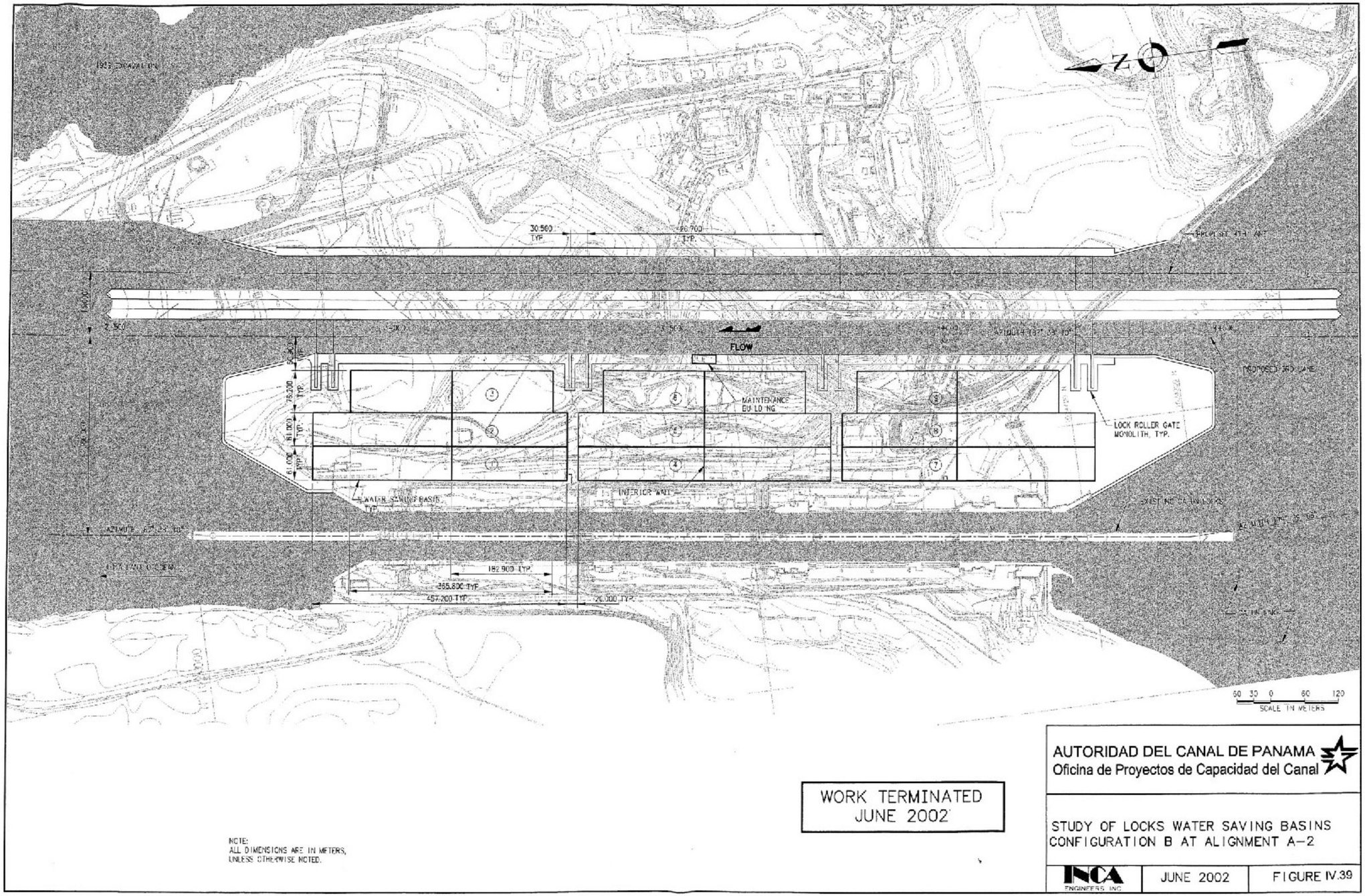


Figure IV.39 – Option 2 Configuration (Structural Features Layout)– Atlantic Side

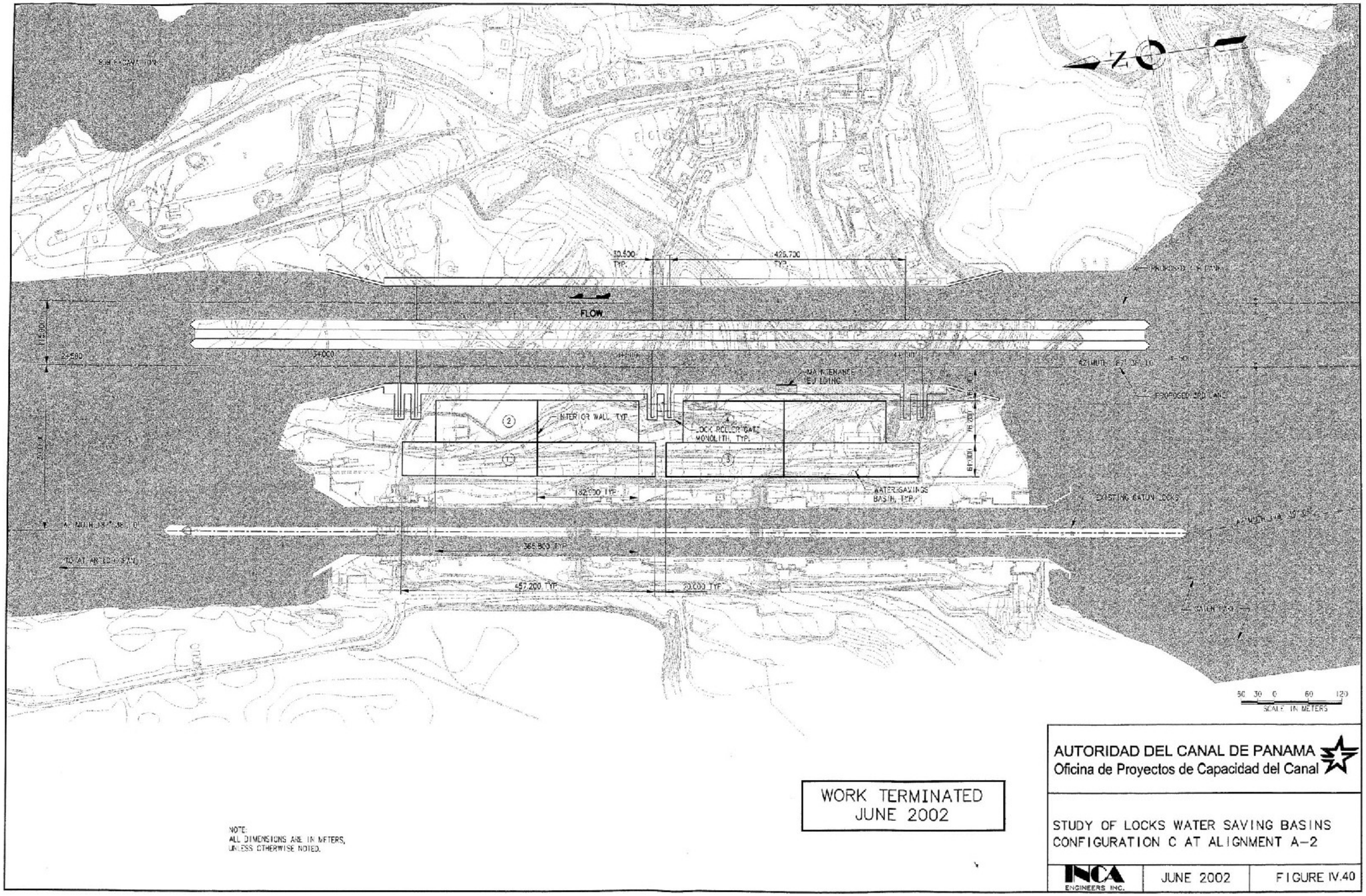


Figure IV.40 – Option 3 Configuration (Structural Features Layout)– Atlantic Side

There are a number of structures located east of the Gatun Locks that will be impacted by the new lock construction. These structures include the Main Office, Machine Shop, Electric Shop, Welding Shop, Pipe Shop, Carpenter Shop and various sheds. These buildings will need to be demolished and rebuilt. Some other affected features include roads, parking lots and railroad tracks. ACP was concerned about two areas in particular; the Locomotive Shop and the tracks for crane access.

The Locomotive Shops are essential for servicing the locomotives that tow vessels through the Gatun Locks. Since there are locomotives on each side of a lock lane, a locomotive shop is needed for each lock wall. Relocating this building is difficult since the operations at Gatun Locks will continue during construction, requiring the ability to service locomotives. Without this building, the only option to service a locomotive is to place it on a barge and transfer it to the shop on the opposite side. This would have a tremendous impact on operations. Due to this issue, ACP decided to preserve this building. To accomplish this, the alignment of the new third lock lane was placed 300 m (984 ft) away from the centerline of the Gatun Locks for Options 1 & 3. For Option 2, this distance was increased to 360 m (1181 ft).

The Gatun Locks utilize mobile cranes that travel on tracks, with a maximum grade of 5%, to each lift. To maintain a 5% grade between each lift at Gatun Locks, the distance between the new and existing locks would need to be increased. This makes centralized opertations more difficult. It would also increase the area impacted by construction of the new locks. Therefore, ACP decided to establish the alignment A-2 based on preserving the Locomotive Shop and replace the mobile crane, servicing the east lane of Gatun Locks, with permanent cranes at each lift.

The impact of the conduit and water saving basin construction on these existing areas will be a function of the footprint of the selected basin configuration.

(2) Soil and Rock Excavation

(*The required soil and rock excavation was not determined as this work was on hold, awaiting determination of conduit size and location when this work was terminated.*)

The existing topography varies significantly along the length of the proposed alignment. In order to minimize basin wall heights, it was assumed that the existing ground surface would be excavated to slope down to the top of basin walls at locations where the basins will be below the existing grade. Where a permanent slope is required immediately adjacent to the water saving basins, a minimum bench width of 5 meters (16 feet) was provided at the base of the excavation (top of the basin) for maintenance vehicle access.

b) Pacific Side

(1) General

(*Conduits are not shown on the drawings as they were not sized prior to termination of this work.*)

(a) Option 1 Configuration

The Option 1 configuration for the water saving basins is shown in **Figure IV.41**. As can be seen from this drawing, Option 1 consists of six side-by-side basins for a three-lift lock, with two basins per lift. The lower basin for each lift is 365.8 m (1200 ft.) long by 76.2 m (250 ft.) wide. The upper basin for each lift is 457.2 m (1500 ft.) long by 61.0 m (200 ft.) wide.

(b) Option 2 Configuration

The Option 2 configuration for the water saving basins is shown in **Figure IV.42**. As can be seen from this drawing, Option 2 consists of six side-by-side basins for a three-lift lock, with three basins per lift. The lower basin for each lift is 365.8 m (1200 ft.) long by 76.2 m (250 ft.) wide. The middle and upper basins for each lift are 457.2 m (1500 ft.) long by 61.0 m (200 ft.) wide.

(c) Option 3 Configuration

The Option 3 configuration for the water saving basins is shown in **Figure IV.43**. As can be seen from this drawing, Option 3 consists of a total of four side-by-side basins for a two-lift lock, with two basins per lift. The lower basin for each lift is 365.8 m (1200 ft.) long by 76.2 m (250 ft.) wide. The upper basin for each lift is 457.2 m (1500 ft.) long by 61.0 m (200 ft.) wide.

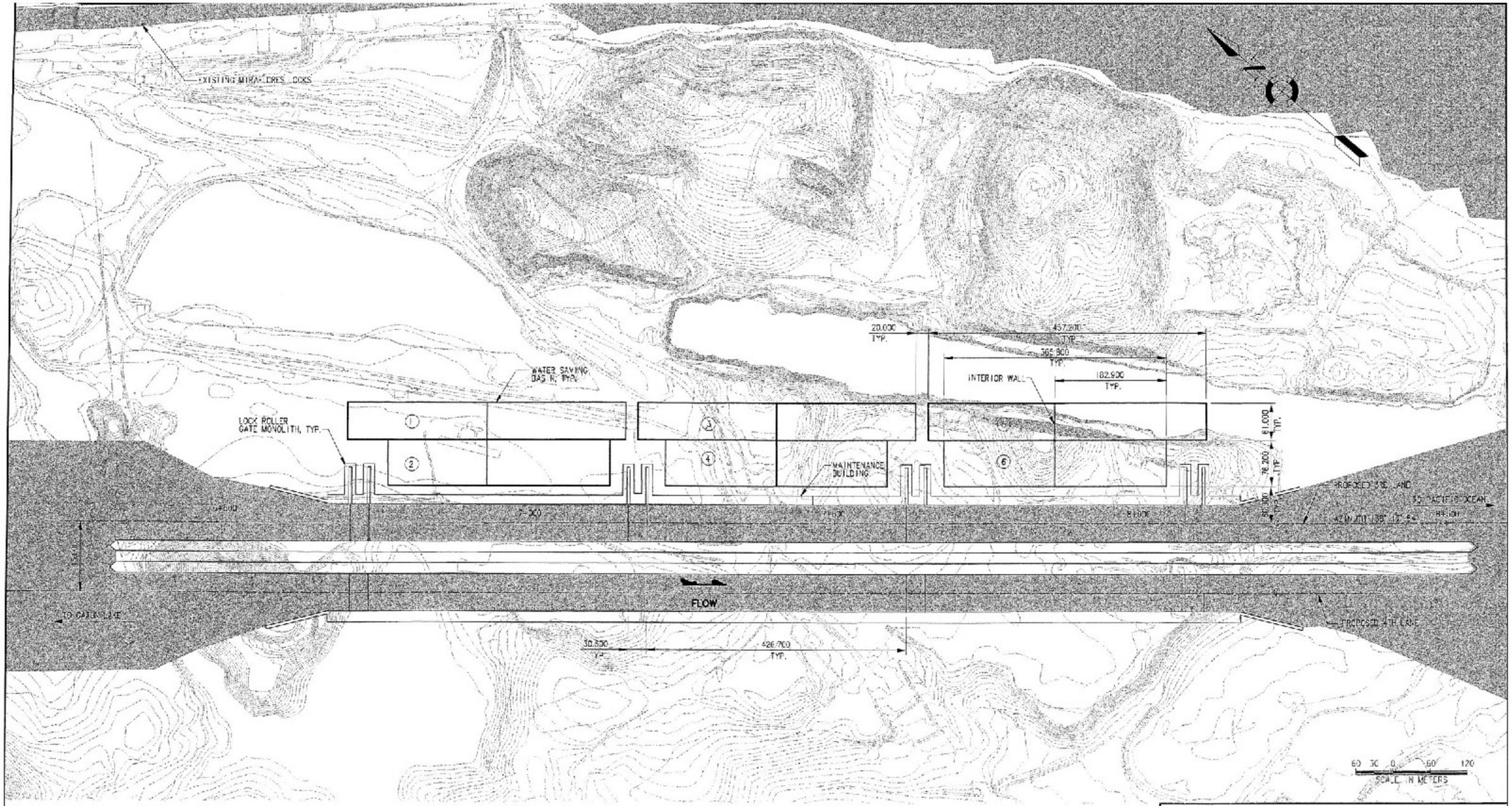
(d) Option 4 Configuration

(*The stacked basins required for Option 4 were not addressed as they were not sized prior to the termination of this work.*)

(2) Soil and Rock Excavation

(*The required soil and rock excavation was not determined as this work was on hold, awaiting determination of conduit size and location when this work was terminated.*)

The existing topography varies significantly along the length of the proposed alignment. In order to minimize basin wall heights, it was assumed that the existing ground surface would be excavated to slope down to the top of basin walls at locations where the basins will be below the existing grade. In order to provide foundation support in areas where the basins will be above the existing grade, select fill material will be placed under and around the basins. Where permanent cuts or fills are required immediately adjacent to the water saving basins, a minimum bench width of 5 meters (16 feet) was provided for maintenance vehicle access.



BASIN	TOP OF FLOOR SLAB ELEV.
1	20.190
2	17.940
3	11.190
4	8.940
5	2.190
6	0.070

NOTE:
ALL DIMENSIONS ARE IN METERS, UNLESS OTHERWISE NOTED.

WORK TERMINATED
JUNE 2002

AUTORIDAD DEL CANAL DE PANAMA
Oficina de Proyectos de Capacidad del Canal

STUDY OF LOCKS WATER SAVING BASINS
CONFIGURATION A AT ALIGNMENT P-I

INCA ENGINEERS INC. | JUNE 2002 | FIGURE IV.41

Figure IV.41 – Option 1 Configuration (Structural Features Layout)– Pacific Side

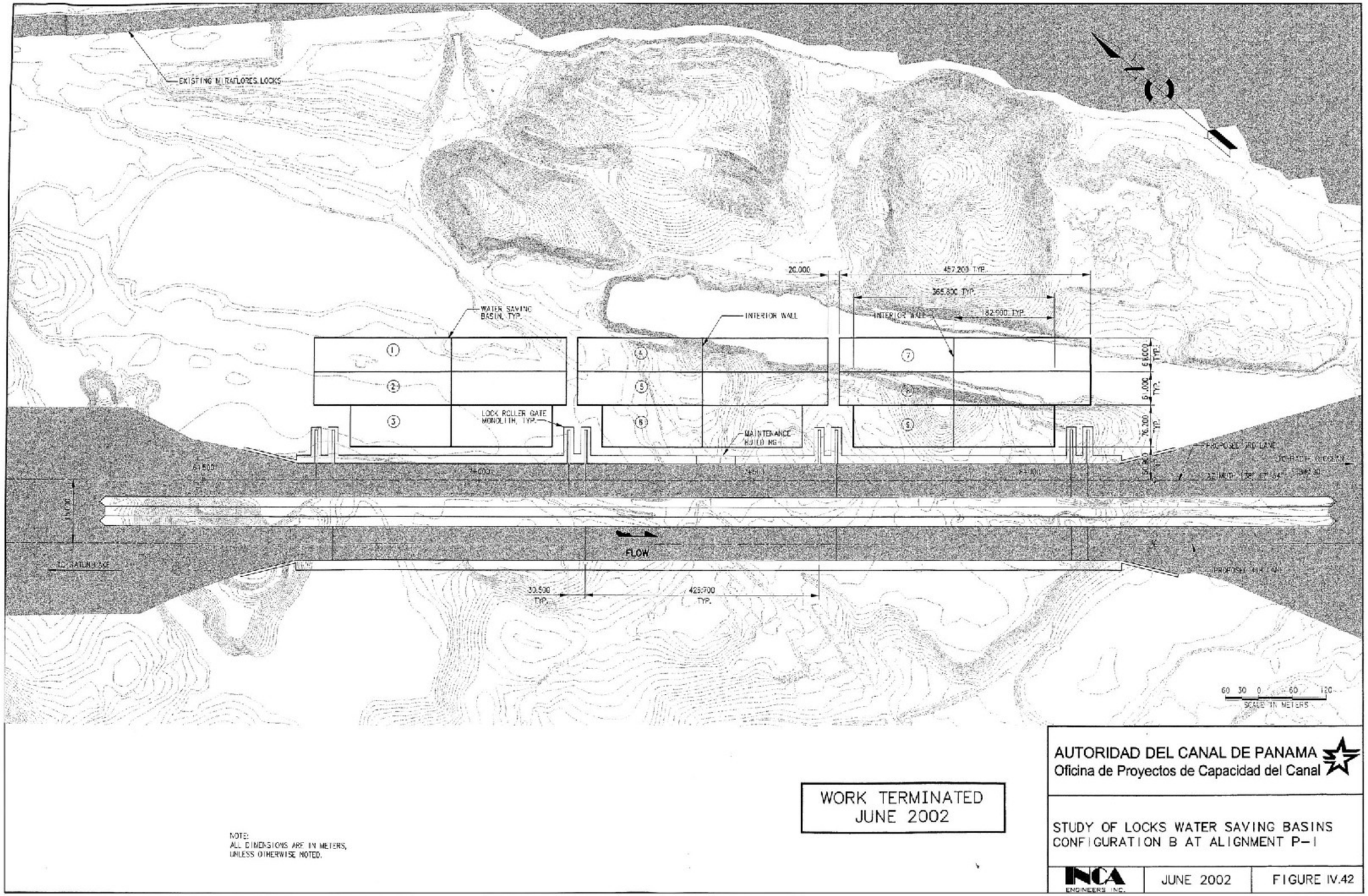


Figure IV.42 – Option 2 Configuration (Structural Features Layout)– Pacific Side

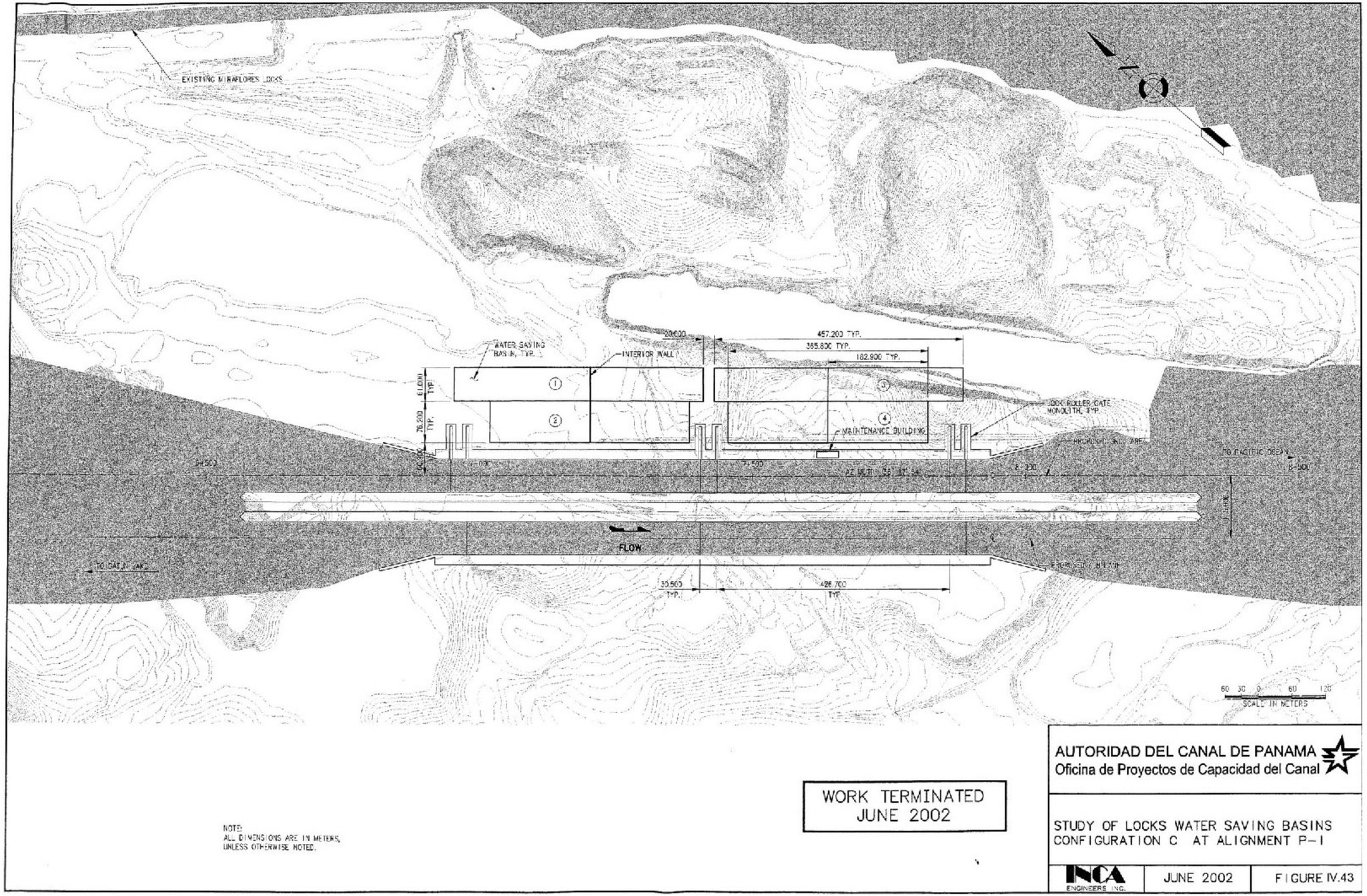


Figure IV.43 – Option 3 Configuration (Structural Features Layout)– Pacific Side