Final Report of the Commission for the Study of Alternatives to the Panama Canal

Volume VI

Operating Characteristics and Capacity Evaluation Pase II

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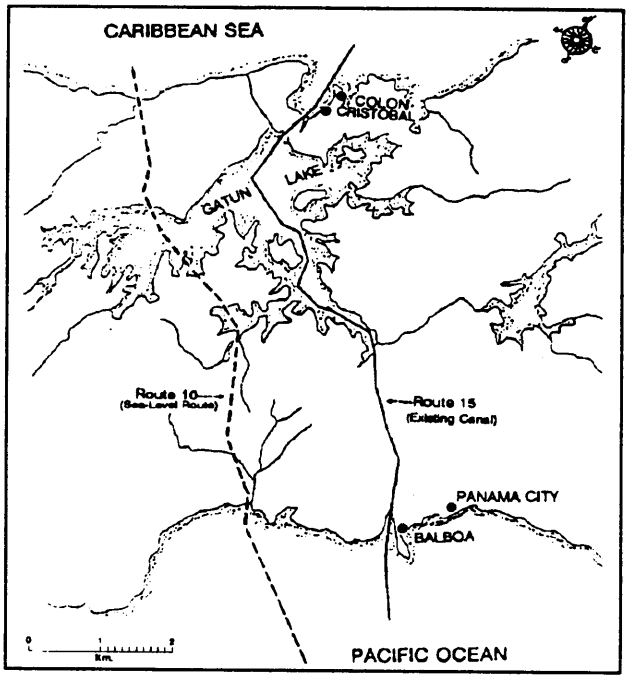
The Commission for the Study of Alternatives to the Panama Canal



Operating Characteristics and Capacity Evaluation Study

Phase 2

FINAL REPORT

COMISION DE ESTUDIO
DE LAS ALTERNATIVAS
AL CANAL DE PANAMA
5 AGO. 1993
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May 1993

TAMS Consultants, Inc.
Oak Ridge National Laboratory
American Bureau of Shipping

Revised 7/15/93

TAMS

May 27, 1993

Commission for the Study of
Alternatives to the Panama Canal
c/o The Secretariat
Banco Union Building
Panama City, Panama

Attn: Mr. Joseph Byrne
Executive Director

Subject: Final Report, OCCE Study

Gentlemen:

We are pleased to submit herewith our Final Report on the Operating Characteristics and Capacity Evaluation (OCCE) Study, Phase 2. The Final Report also incorporates principal results and conclusions from OCCE, Phase 1. The study was prepared in accordance with our Agreement with the Study Commission dated August 12, 1991, as amended August 25, 1992.

The OCCE Study is one of the components of the Study of Alternatives to the Panama Canal. The analyses herein have been based on traffic projections prepared under the Commerce and Traffic Projections component study and also incorporates certain features from the Engineering and Cost Estimates component study. A major tool in our capacity analysis has been the Waterway Analysis Model, which has been adapted from past applications to suit Panama Canal conditions.

A second major element of our work has been to investigate currents in a proposed sea-level canal that would be generated by the differences in tides between the two oceans, to evaluate their impact on navigation, and to suggest means of ameliorating these currents. After analysis using our in-house computer model LATIS, we have concluded that a positive means of control of currents in the form of tide gates or locks is required to maintain currents at a tolerable level. An analysis was also made of sediment transport in a sea-level canal and its impact on maintenance dredging.

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Recommendations were made for navigation support systems and estimates of their costs were prepared. In addition, estimates of the volumes of fresh water consumed during high-rise lockages were prepared using the WAM to obtain the number of annual chamber operations and lockages.

Regarding capacity, it was concluded that the existing canal, with the Gaillard Cut widened to 630 feet (referred to as the status quo case) will reach capacity by year 2020 and that improvements will be needed to satisfy vessel traffic needs thereafter.

All of the high-rise lock canals studied would have sufficient capacity to meet year 2060 needs. A single-lane, Route 10, sea-level canal with either tide gates, or two locks at the Pacific end, would have sufficient capacity for year 2060 traffic needs, if operated in conjunction with the status quo canal.

Capacity is, of course, only one of many factors that influence feasibility--others being: costs, benefits to Panama and world navigation, environmental effects, disruption of operations, time of construction, safety and reliability.

We gratefully acknowledge the cooperation we have received from officials and staff of CAS, the Panama Canal Commission and other public agencies and other consultants involved in the project, including SINBOL, the WEFA Group and YEC.

We also gratefully acknowledge the contribution to the study of subcontractors to the prime team, including: the U.S. Army Corps of Engineers, Huntington, WV, the University of Tennessee, SoftTEACH Corporation and Prof. Haruzo Eda of the U.S. Merchant Marine Academy, Kings Point, NY.

Very truly yours,

TAMS CONSULTANTS, INC.

Albert T. Rosselli

Albert T. Rosselli
Senior Vice President
Project Director

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SUMMARY

INTRODUCTION

The Operating Characteristics and Capacity Evaluation (OCCE) Study is one of a group of studies of future alternatives to the Panama Canal sponsored by a study commission formed by the governments of Panama, the United States and Japan (CAS). The basic purpose of the OCCE study was to evaluate the traffic capacities of various canal alternatives.

The OCCE Study used inputs from the traffic projections and engineering component studies and defined elements needed for engineering, economic and financial analyses being undertaken by others. The basic tool for the OCCE effort has been a simulation model developed by the U.S. Army Corps of Engineers for use on the U.S. inland waterways system and adapted under OCCE for analyses of the operating characteristics and capacities of the existing Panama Canal and possible future alternatives.

The Study was conducted in two phases. For the prescreening of alternative canal schemes that was accomplished in Phase 1, a range of assumptions were used that reflected an extension of experience with the present Panama Canal. Model runs in Phase 2 involved more rigorous analyses of ship arrival patterns and the impact of normal interruptions and mishaps and the dynamic assignment to a route, of ships confronted with an alternative. The Phase 2 runs were used to evaluate in greater detail a limited number of alternative plans selected by CAS from the results of Phase 1 capacity, traffic forecasts and engineering studies.

In addition to capacity, the scope of work also included other types of studies, including: evaluation of currents that would be generated in a sea-level canal by tidal differences between the two oceans and means of ameliorating these currents, estimation of sedimentation in the sea-level canal alternatives, preparation of conceptual plans and estimates of costs for navigation support systems and estimates of fresh water consumed during lockages.

For the purpose of Phase 1 of OCCE, many alternative plans proposed historically were synthesized into two routes (Figure 1-1) and four basic groups: High-Rise Lock Canal; Low-Rise Lock Canal; Sea-Level Canal; and Status Quo. The Status Quo Canal is the existing canal with the authorized widening of the Culebra Cut (also known as the Gaillard Cut) to 630 feet completed.

Alternative nominal maximum ship sizes were considered, ranging from 65,000 DWT to 300,000 DWT during Phase 1. The 65,000 DWT class was considered the maximum size for the Status Quo Canal. The high-rise and low-rise lock canal plans were analyzed for alternative maximum sizes of 100,000 DWT, 150,000 DWT and 250,000 DWT. Under the Sea-Level Canal plans, the alternative maximum

sizes considered were 150,000 DWT, 250,000 DWT and 300,000 DWT. The capacities of approximately 25 alternative cases were evaluated during Phase 1.

During Phase 2, the high-rise locks and sea-level alternatives listed in Table 1-2 and shown schematically in Figures 1-2 and 1-3 were evaluated. All of the cases involve the continued use of the existing locks; the sea-level cases would be used in conjunction with the status quo canal. Maximum ship sizes considered were 200,000 DWT for the high-rise lock alternatives and 250,000 DWT for the sea-level alternatives.

OPERATIONAL CRITERIA, PROCEDURES AND PARAMETERS

The principal criteria governing Canal operations are: safety, capacity, costs and water use. Safety, of course, is foremost. Capacity is considered adequate if ships' times in canal water do not exceed 24 hours. The canal is operated as economically as possible, except, if excessive congestion is expected, more costly "relay" operations are employed at the multi-stage locks; these involve the use of additional crews. Water use is not a problem except during particularly dry seasons. With increased numbers of lockages in the future, and the possible addition of new, larger locks, water use would take on added importance.

The general operating procedure is "first come, first served". However, this procedure is modified by various conditions. For example, large ships and ships carrying hazardous cargoes are not permitted to navigate through the Culebra Cut at night, nor can they pass or overtake another ship in the Cut. There is also provision for reserved and preference transits for ships traveling on critical schedules.

Among the key operating parameters that impact on capacity are: size of vessel, vessel arrival rates, one-way or two-way operations, lock service times, and traffic management procedures. For sea-level canal alternatives, maximum allowable vessel speed, vessel spacing and length of operating cycles for one-way segments are also of critical importance.

ANALYSIS OF VESSEL ARRIVAL, PREPARATION AND TRAVEL TIME

The principal source of data on vessel arrival patterns and transit times was the Ship Data Bank (SDB) compiled by the Panama Canal Commission (PCC). The SDB contains data on every ship transit through the Canal, including the times of passage at key control points in the system, such as the locks and the Culebra Cut. The SDB records for 13,611 vessel transits for the year 1990 were analyzed in this study. The SDB data were supplemented by data collected at the locks over a two week period in 1991 under the OCCE study.

The SDB data were used to investigate vessel arrival patterns, and to derive detailed estimates of vessel transit times, channel speeds, and locking times, for input to the Waterway Analysis Model and for model calibration purposes. The

data collected on-site were used to assist in dividing the locking times into the specific time elements required for input to the model, and to guide the interpretation and usage of the SDB data.

Some of the principal conclusions of the data analyses conducted are as follows:

Ship arrivals were found to be distributed randomly throughout the year; that is, there were no strong seasonal or monthly patterns evident in the data.

The hourly pattern of ship underway times (the beginning of transit) strongly reflected the current scheduling practices used to restrict (for safety reasons) meetings and night passage of large ships through the Culebra Cut. The pattern of underway times did not vary significantly between the rainy season and the dry season.

Northbound and Southbound transit times were found to be different, with an average of 12.5 hours Northbound and 9.8 hours Southbound. Consequently directional differences were maintained in the model input data.

The average movement time through the Canal was found to be between eight and nine hours, which is consistent with the segment travel times used by the PCC for ship scheduling. The remaining time is waiting time.

The time interval between the arrival of a ship and its beginning of transit was also investigated, both from the SDB records and through conversations with knowledgeable individuals in Panama. This interval, on the average, exceeded 11 hours in 1990. There are minimal operational and administrative delays during this period. Rather, most of the time is accounted for by discretionary vessel activities, and by the aforementioned scheduling practices related to restrictions on passage through the Cut.

As a result of these observations, a ship generation and scheduling program was developed to prepare vessel traffic lists for input to the Waterway Analysis Model. This program uses random underway times for future systems with the Cut restrictions lifted, or allows ship scheduling to correspond approximately to the present procedures.

SEA-LEVEL CANAL - TIDAL HYDRAULICS AND NAVIGATION

Studies were made to analyze the tide levels and currents in a sea-level canal generated by changes in the tides of the two oceans. The TAMS program LATIS was used to formulate a mathematical model of the canal. The spring tides in the Pacific range from about +10.3 to -9.8 ft., whereas at the Atlantic end the range is only about +1.2 to -0.7 ft.. This difference of levels would produce currents in an open channel ranging from about 4 knots at the Pacific end to more than 5 knots at the Atlantic end. The maximum allowable currents for the safe navigation of the

very large ships, however, are about 2 knots for head currents and 1 knot for following currents.

The Vergara alternative, which would employ a large embayment at the Pacific end of the canal to mitigate tidal effect was investigated, but the analysis indicated that although currents in the canal would be reduced, the reduction would not be sufficient for safe navigation; moreover, very fast currents would be generated at the entrance to the embayment area.

It was concluded that a system of positive closure involving two tide gates, or locks, is needed to control currents. Tide gates would be operated only at slack water, which occurs every 6¼ hours and operating cycles would be keyed to this rhythm. The canal with locks can operate independently of the tide cycles. However, a cyclical operation is necessary because of the long length of one-way channel. A 12½ hour cycle was selected for analysis of the lock alternatives.

THE WATERWAY ANALYSIS MODEL

The Waterway Analysis Model (WAM) has been in use by the U.S. Army Corps of Engineers for more than ten years. The purpose of the WAM is to represent on a computer the operation of a waterway system in transporting waterborne cargo. WAM is a relatively large and detailed simulation model, providing explicit representation of individual waterway facilities, cargo consignments, and vessels. The WAM was originally developed to simulate shallow draft barge traffic on the U.S. inland waterways. The model has been used extensively to simulate parallel locks, and thus is directly applicable to the multi-lane Panama Canal operations.

The Waterway Analysis Model has two types of input data. The system description input data describe the waterway network (ports, locks, interconnecting channels), the vessel fleet, and the commodity classes to be transported. The external event input records are read into the model during the simulation process and trigger the occurrence of events, including the introduction of vessel traffic into the system and initiation of lock downtime periods. The simulation program is the operational heart of the model; it processes the input data, produces playback reports, initializes the waterway system, processes each shipment from origin to destination, records statistics for generation of performance output reports, and creates files for post-processing by other programs. The output processing routines of the program use statistics gathered during the simulation to generate performance reports on lock utilization and delay, vessel utilization, port activity, detailed traffic summaries, and other optional reports specified by the user.

The WAM was used with minor modification to simulate the operation of the Panama Canal for Phase 1 of this study. Various program modifications were made for more accurate simulation in Phase 2.

The WAM data structure was directly usable, without change, for representing both the existing canal and the proposed sea-level canal. The system consists of a port at each end, locks at Gatun, Pedro Miguel, and Miraflores, a restricted channel to represent the Culebra Cut, and the intervening reaches between these elements. The locks are represented as dual chamber facilities, where each lane is considered to be a single chamber. Configurations with a third lane of locks were represented directly as a branch in the network, with the new lock located in this branch.

The principal modifications made to the WAM for better representation of the high rise locks alternatives involved modeling of relay operations at the locks and the introduction of dynamic route assignment. Relay operations reduce throughput time, and were, therefore, included for purposes of estimating capacity. The WAM was modified to permit switching into and out of relay operations on a scheduled or demand driven basis. Relay operations commence if justified by the queue size at the start of each eight-hour shift. Additionally, relay operations are started at one lane of dual-lane locks when the other lane is down. The WAM was also modified to include internal decision rules for assigning a ship to the next sector of the network in cases where parallel routings are possible, eg. the third locks plans. The model bases the routing choice on the relative expected times to transit the next set of possible sectors. The output of the WAM was expanded to record the route selected by each vessel.

Also, for Phase 2 of the study, the WAM was modified to incorporate new software modules to model the formation and operation of ship convoys through the proposed sea-level options for the Panama Canal. This effort included the development of algorithms to simulate dynamic ship assignments to alternative routes, including the sea-level and status quo options. Dynamic ship assignment is based on the answer to the following question: How long will it take for a ship to traverse the canal using each of the alternative routes? The routing module accounts for the ship arrival time, the queue of ships awaiting passage, and the schedule in effect for directional assignment of the one-way channel.

The WAM was calibrated by comparing outputs for a simulation of the system in 1990 with the corresponding operating statistics derived from the Ship Data Bank (SDB) records. The locking times, segment travel times, and overall transit times were found to be in good agreement with the SDB data. Thus the model calibration was deemed to be good enough to proceed with the simulation of the alternative conceptual plans.

PREPARATION OF SIMULATION

Given the calibrated Waterway Analysis Model (WAM) and the results of the analysis of the Ship Data Bank records, a series of further data analyses and assumptions were made to prepare the inputs needed to simulate the performance of the alternative conceptual plans for the Panama Canal under different future vessel

traffic levels. These data and analyses include the future mix of vessel traffic, vessel characteristics, and lock sizes and operating times for the new locks plans.

Vessel mix forecasts for the years 2020 and 2060, for maximum vessel sizes of 65,000, 150,000, and 250,000 DWT were obtained from the Phase 1 vessel traffic forecasts prepared by the commodity traffic projections contractor. The vessel mix for the 200,000 DWT maximum vessel size was interpolated from the 150,000 and 250,000 DWT vessel size projections. Considering all of these cases, the number of ship transits forecast for the Canal range from about 18,000 ships in 2020 to 25,000 ships in 2060.

Vessel characteristics, including length, beam, maximum draft, and engine power, were obtained by reviewing the designs of commercial ships built worldwide in recent years. For the larger ship sizes introduced for the third locks and sea-level canal plans, observations of ship designs were augmented by data on ship stopping behavior obtained from ship trial runs and from computer simulation. These latter sources also provided data on minimum ship stopping times, which were used to develop input data on minimum ship separations for the sea-level canal WAM simulations.

Lock chamber sizes for the proposed new locks were developed by considering the minimum clearances between the ship and the lock chamber required for efficient operations. Locking times were then estimated by considering the operations in the existing locks which feature similar vessel-to-lock clearances.

Simulation runs for each of the conceptual alternatives were made by preparing an input vessel traffic list with the requisite number of ships, using the vessel traffic mix for the appropriate year (usually 2060) and maximum vessel size, and configuring the network and downtime input files to represent the appropriate system. Simulation runs were made for two different traffic levels for the third locks plans, and for three traffic levels for the sea-level canal options. In all cases, the new systems were run in parallel with the status quo system, and vessel traffic was dynamically assigned to the alternative routes based on current simulated operating conditions over each route.

CAPACITY OF ALTERNATIVE ROUTES

The capacity of a canal alternative is a function of delay or transit time (travel plus delay). A higher capacity can be achieved at a cost of longer delays and greater congestion. The level of delay is a function of the rate of ship arrivals, compared with the rate of ship transits. Delays and transit time increase gradually at low traffic volumes but accelerate rapidly as traffic continues to build. The relationship is characterized by a hyperbolic curve. Capacity of an alternative is actually estimated as the number of ships that can transit the canal at an acceptable delay or transit time.

Case 8A, with a longer single-lane segment than Case 8 (55.5 Km vs. 40 Km) would have less capacity than Case 8, because, with a maximum convoy speed of 13 Km/hr., there would be insufficient time for a full convoy to transit the longer single-lane segment and allow the next convoy to enter during the 6¼ hour cycle of gate openings and closings. The result is that either cycles would have to be skipped, or, convoy lengths would have to be shortened. A longer cycle time (12½ hours) would produce higher capacity, but would require dredging deeper channels at the Pacific side. Nevertheless, the capacity of Case 8A is adequate to meet year 2060 forecasted needs.

For the High-Rise Canal cases with a two-lane Culebra Cut (cases 2-5) the model schedules vessels to begin transit immediately upon arrival. For the single-lane Culebra Cut cases (6 & 7), however, large ships arriving at night do not start their transit until early morning, using the logic outlined in Chapter 3. This waiting time is added to any transit delay that results from congestion, to arrive at a total delay.

The Sea-Level Canal alternatives are based on a cyclical operation. For the combined sea-level and status quo alternatives, because actual travel times differ along the two routes, it was more appropriate to use transit time (travel plus delay) as a measure, rather than delay time alone. This is also compatible with the dynamic route assignment logic in the model, which attempts to equalize transit time on the two routes.

In all cases, except the status quo, the 2060 ship mix was used in the model.

Alternative delay times of six hours and ten hours were assumed as the basis of capacity for the status quo and high-rise canal cases (1-7) and transit times of 15 hours and 19 hours for the combined sea-level/status quo cases (8, 8a, 9, 9a, 9b and 10). Since the travel (non-delay) portion of transit time through the status quo system is approximately 9 hours, these criteria are consistent.

The resultant capacities of the Phase 2 alternatives are presented in Table 7-4, which is reproduced herein.

SEDIMENT TRANSPORT

The sediment movement in the canal is influenced by several factors. River discharge, ocean tides, interaction of currents and waves, ship generated waves, construction of breakwaters, operation of the tide gates, and land use are some important causes that have to be considered in estimating the amount of sediment transported in a year. However, the above processes, illustrated in Figure 8-7, can be broken into several parts, as follows: (a) the canal zone between the coasts where the tides and the river flows interact, (b) the coastal zone where the waves are predominant, and (c) the entrances to the breakwaters where the combined effect of currents and waves are felt. The operation of the tide gates and locks has also been taken into account in a schematic manner.

TABLE 7-4
ESTIMATED CAPACITY

Study Case	Conceptual Alternative	Maximum Ship Size 000s DWT	No. of New Lanes		Capacity-Annual Transits No. of Ships		Capacity M Tons	
			Channel	Lock Chambers	6 Hr. Delay*	10 Hr. Delay*	6 Hr. Delay	10 Hr. Delay
1	Status Quo	WEFA 65	-	-	16,100	17,000	374	395
1a	Status Quo	PCC 65	-	-	14,500	15,300	396	418
2	High-Rise Locks (85ft)	150	2	1	32,500	34,600	978	1,041
3	High-Rise Locks (85ft)	150	2	2	48,300	51,300	1,455	1,545
4	High-Rise Locks (85ft)	200	2	1	33,200	35,300	999	1,062
5	High-Rise Locks (85ft)	200	2	2	51,100	54,300	1,559	1,657
6	High-Rise Locks (85ft) Culebra Cut single-lane	150	2	1	31,200	34,400	941	1,038
7	High-Rise Locks (85ft) Culebra Cut single-lane	200	2	1	31,600	34,600	963	1,055
8	Route 10 Tide Gates & Status Quo	250	2/1	**	42,500	44,000	1,318	1,364
8a	Route 10 Tide Gates & Status Quo	250	1/1	**	34,300	35,800	1,063	1,110
9	Route 10, Pacific Locks & Status Quo	250	1	3	33,300	41,700	1,032	1,293
9a	Route 10, Pacific Locks & Status Quo	250	1	3***	34,300	45,200	1,063	1,401
9b	Route 10, Pacific Locks & Status Quo	250	1	1	20,800	24,000	645	744
10	Route 10, Pacific Locks & Status Quo	250	1	4	37,000	47,500	1,147	1,472

NOTE: See Figures 1-2 and 1-3 for schematics of alternative plans. Culebra Cut is two lanes, unless noted otherwise. Case 8a is the same as Case 8, except that a single-lane channel would be substituted for the 2-lane channel from the Atlantic end coastline to the north tide gate.

* The capacities of the sea-level canal cases (8 through 10) are based on transit times of 15 and, alternatively, 19 hours.

** Tide Gates

*** One double length chamber plus one standard chamber in parallel.

Several computer programs were used in the study. Each one had a unique application, namely,

- LATIS to determine hydraulic variables such as velocity, water depth, and create the necessary input data for ROUTES;
- ROUTES to estimate sedimentation depths along the canal with the output from LATIS;
- BEACHES to estimate shoreline changes.

The models, which are idealizations of the physical process, give estimates which have to be interpreted with judgment. This is due to the underlying assumptions in the model, input data, boundary conditions, and the numerical scheme used in the algorithm. The values of several parameters were assumed, based on available literature and engineering judgment.

The following results were achieved:

(a) The model indicated that annual dredging in the canal section between the coasts for the tide gate and lock alternatives would be in the range of 450,000 m^3/yr, due to the effects of sediment inputs from the rivers and the tidal transport. In the absence of river sediments, the model results indicated a 30% reduction in the quantity of sediment to be dredged.

(b) Bathymetric data were used to estimate sedimentation rates for the existing canal. The locations, the annual sedimentation rates per kilometer and the extrapolated values for a canal of 58 km long are summarized below.

	Sediment Deposition/Year	
	190m Wide Canal (m^3/km)	58 km Stretch (m^3)
Atlantic Entrance	9,500	551,000
Balboa Inner Harbor	12,800	742,000
Pacific Entrance	11,850	687,300
Miraflores Lake	9,550	--

Based on the above table, a mean sedimentation rate of 660,000 m^3/yr is an acceptable value.

(c) On the Atlantic side, the model predicted an annual littoral drift of 12 x 10^6 m^3/year. This would result in an accretion on the southern breakwater of 100 m, while the depletion on the northern breakwater

is 60 m per year. In other words, the shoreline adjacent to the southern breakwater moves outward along the breakwater at the rate of 100 m per year building up a beach from the trapped littoral drift. At this rate, with the length of the breakwater being 2.6 km, it will be 25 years or so after construction before any of the material transported by littoral currents enter the canal.

(d) The model predicted neither accretion nor depletion on the Pacific side. However, some accretion and depletion are expected. Climatic data, especially very close to the site, should be collected and a detailed study conducted.

For planning and estimation of annual dredging costs, a volume of 550,000 m^3/year could be used.

NAVIGATION SUPPORT SYSTEMS

Recommendations are made in several areas to improve navigation conditions, including: range lights, buoys and beacons in channels, tug assistance for vessels transiting narrow channels, for lock approach and entry and for the sea-level canal, lengths of lock approach walls, locomotives on lock walls, ship tie-up facilities at locks and at intervals along the sea-level canal.

The capital and operating costs of the proposed navigation support systems are also presented (see Chapter 10).

FRESH WATER CONSUMPTION - HIGH-RISE LOCKS

An analysis was made of the fresh water consumed in lockages of the high-rise locks for alternative canal cases 2, 4 and 8, in the years 2020 and 2060.

The Waterway Analysis Model was run for the required cases using the WEFA forecast of ship transits to obtain the number of annual chamber operations and lockages. The type of operation used was based on optimizing capacity, rather than minimizing water consumption. The results, in millions of cubic meters (M.c.m.) annually, are shown below:

	Case	Year 2020	Year 2060
2	High-Rise Locks (150,000 DWT)	6,381	8,029
4	High-Rise Locks (200,000 DWT)	7,214	8,965
8	Status Quo Route (Used with Sea-Level Canal, Tide Gates)	1,731	2,033

CONCLUSIONS AND RECOMMENDATIONS

Sea-Level Canal Navigation

- Maximum allowable currents in a sea-level canal for the safe navigation of 150,000 DWT ships and larger are 2 knots for head currents and 1 knot for following currents.

- To limit tidal currents to safe levels, a closure system would be required involving either tide gates, or locks situated close to the Pacific shore.

- To achieve maximum capacities with significant lengths of single-lane canal, scheduling of ship transits in convoy formations would be required.

- The cycle time for tide gate operations should coincide with the half-tide cycle, or every 6¼ hours. For a convoy traveling at a speed of 7 knots, the optimum spacing of the tide gates joined by a single-lane canal is about 40 Km. The ship convoy length should not exceed 35 Km.

- With the above configuration and operation, ships entering and exiting the canal at the Pacific side could be scheduled such that they would always confront a head current, not a following current. Because the canal would be shielded from the Pacific low tide, the Pacific approach channel depth could be based on mean-sea-level rather than low water.

- In a sea-level canal controlled by locks, the cycle time for convoys would be independent of the tide cycle; i.e., the water level at both sides of the lock gates could always be equalized, regardless of the tide level. An optimum balance should be sought, therefore, between limiting turnovers, which are wasteful of capacity and avoiding excessive delay time for ships that must await a following convoy.

- Ships 150,000 DWT and larger should be assisted through their transit with a 6,000 hp tug at the stern. Emergency ship tie-up stations should be provided and stand-by tugs should be placed at strategic intervals along the canal to assist in the event of break-downs.

Capacity

By comparison of the capacities indicated in Table 7-4 with the vessel mix forecasts of Table 6-1, the following are concluded:

- The capacity of the Status Quo Canal will be exceeded by year 2020.

- All of the High-Rise Canal alternatives (cases 2, 3, 4, 5, 6 and 7) have adequate capacity for vessel transit needs to year 2060, including those with a single lane of new locks and a single-lane Culebra Cut.

- For a single lane of new locks, there is no significant difference in capacity between maximum ship sizes of 150,000 and 200,000 DWT.

- The High-Rise Canal alternatives with two new lanes of locks (cases 3 and 5) have redundant capacity.

- The delays imposed by a single-lane Culebra Cut are small compared to the lock delays; therefore, cases 6 and 7 result in only a slightly lower capacity than the cases with a two-lane Cut and their capacities are still greater than forecasted traffic. The primary benefit of a widened Cut, therefore, would be improved safety rather than increased capacity.

- The combined sea-level/status quo cases 8, 8a, 9, 9a and 10, i.e., all of the cases studied except case 9b, single lock at the Pacific end, have enough capacity for vessel transit needs through the year 2060.

- Case 8A, with a longer single-lane segment than Case 8 (55.5 Km vs. 40 Km) would have less capacity than Case 8, because, with a maximum convoy speed of 13 Km/hr., there would be insufficient time for a full convoy to transit the longer single-lane segment and allow the next convoy to enter during the 6¼ hour cycle of gate openings and closings. The result is that either cycles would have to be skipped, or, convoy lengths would have to be shortened. A longer cycle time (12½ hours) would produce higher capacity, but would require dredging deeper channels at the Pacific side. Nevertheless, the capacity of Case 8A is adequate to meet year 2060 forecasted needs.

- Based on the transit time criteria selected (15 and alternatively, 19 hours), case 9b -- the status quo plus a single-lane sea-level canal with a single lock at the Pacific -- would have insufficient capacity to meet the forecasted traffic levels. A similar system with two locks at the Pacific probably would satisfy the demand.

The Sea-Level Canal cases all produce results in which the status quo operates under highly congested conditions, to allow ships to avoid the long delays that are possible due to the fixed cycles of traffic through the single lane. For case 8, congestion delays are balanced between the two parts of the system. For cases 9 and 10, however, the 15 and 19 hour criteria for transit time reflect relatively uncongested conditions in the sea-level section, indicating redundant capacity which could be realized if a less restrictive travel time criterion were applied.

CHAPTER 1

INTRODUCTION

The Operating Characteristics and Capacity Evaluation (OCCE) Study is one of a group of studies of future alternatives to the Panama Canal sponsored by a study commission (CAS) formed by the governments of Panama, the United States and Japan. The basic purpose of the study was to evaluate the traffic capacities of the various canal alternatives.

The OCCE Study used inputs from the traffic projections and engineering component studies and defined elements needed for engineering, economic and financial analyses being undertaken by others. The basic tool for the OCCE effort has been a simulation model developed by the U.S. Army Corps of Engineers for use on the U.S. inland waterways system and adapted under OCCE for analyses of the operating characteristics and capacities of the present Panama Canal and alternatives.

The Study was conducted in two phases. Successive analyses were made with an increasingly refined model, more data and more intensive preparatory statistical analyses and study of potential congestion, in order to gain greater levels of precision. For the prescreening of alternative canal schemes that was done in Phase 1, a range of assumptions were used that reflected an extension of experience with the present Panama Canal. Model runs in Phase 2 involved more rigorous analyses of ship arrival patterns and the impact of normal interruptions and mishaps and extraordinary events and the dynamic assignment of ships to a route when they are confronted with an alternative. The Phase 2 runs were used to evaluate in greater detail a limited number of alternative plans selected by CAS from the results of Phase 1 capacity, traffic forecasts and engineering studies.

In addition to capacity, the scope of work also included other types of studies, including: evaluation of currents that would be generated in a sea-level canal by tidal differences between the two oceans and means of ameliorating these currents, estimation of sedimentation in the sea-level canal alternatives and preparation of conceptual plans and estimates of costs for navigation support systems.

OCCE - PHASE 1

Over the course of over half a century of study, many alternatives have been proposed and studied for increasing the capacity of the existing Panama Canal. These alternatives incorporated a range of different routes, physical layouts and operating concepts, that would accommodate a range of vessel sizes, extending from the present 65,000 DWT up to 300,000 DWT.

For the purpose of Phase 1 of OCCE, many alternative plans proposed historically were synthesized into two routes (Figure 1-1) and four basic groups:

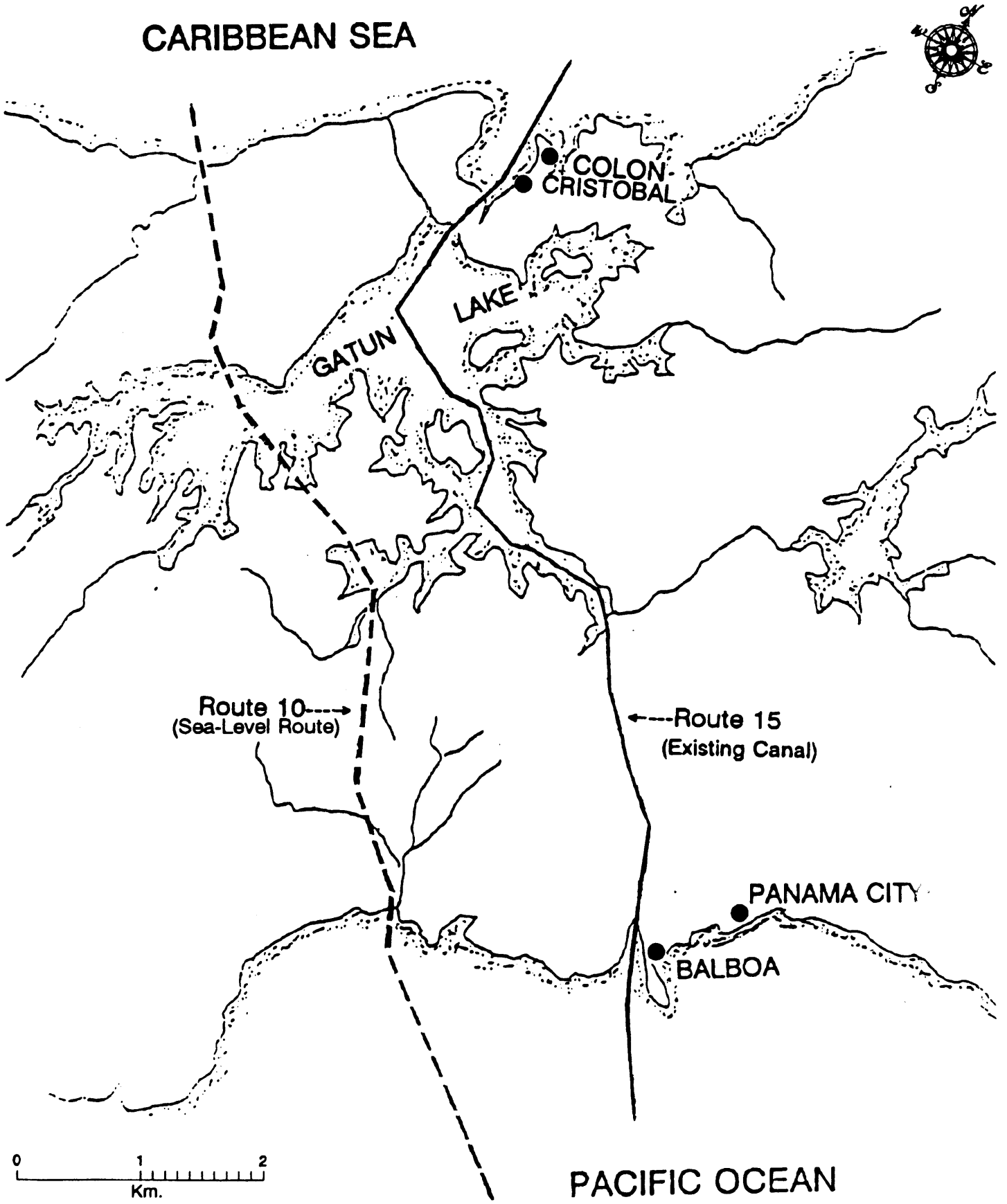

CARIBBEAN SEA
COLON
CRISTOBAL
GATUN
LAKE
Route 10
(Sea-Level Route)
Route 15
(Existing Canal)
PANAMA CITY
BALBOA
0
1
2
Km.
PACIFIC OCEAN

FIGURE 1-1

A. High-Rise Lock Canal;
B. Low-Rise Lock Canal;
C. Sea-Level Canal;
D. Status Quo.

The Status Quo Canal is the existing canal with the authorized widening of the Gaillard Cut to 630 feet completed.

The basic source for the characteristics of the alternative conceptual plans evaluated under the Phase 1 OCCE Study was Table 1-1, prepared by CAS and their consultants SINBOL, a consortium responsible for coordination of the component studies.

Five alternative nominal maximum ship sizes were considered, ranging from 65,000 DWT to 300,000 DWT. The 65,000 DWT class was considered the maximum size for the Status Quo Canal. The high-rise and low-rise lock canal plans were analyzed for alternative maximum sizes of 100,000 DWT, 150,000 DWT and 250,000 DWT. Under the Sea-Level Canal plans, the alternative maximum sizes considered were 150,000 DWT, 250,000 DWT and 300,000 DWT.

The Terms of Reference also required analysis of tidal currents and the requirements for safe navigation of large ships in a Sea-Level Canal. This analysis demonstrated that positive means of control such as tide gates or locks would be needed to reduce currents to safe navigating levels. As a result, only cases providing such control were evaluated by WAM, as specified by CAS, as follows:

- single-lane canal 58 km long flanked by tide gates operated on a 12½-hour cycle, with two-lane approaches in the Pacific and Atlantic;
- two-lane canal throughout with one tide gate close to the Pacific end and the other gate 40 km towards the Atlantic, operated on a 6¼-hour cycle;
- two-lane canal except for a 40 km single lane section with the southern end close to the Pacific flanked by tide gates, operated on a 6¼-hour cycle;
- a single-lane canal with parallel ship locks at the Pacific entrance;
- a two-lane canal with parallel ship locks at the Pacific entrance.

The last two cases above were considered only for ship mixes with a maximum ship size of 250,000 DWT.

CAS also suggested analysis of:

TABLE 1-1
CONCEPTUAL ALTERNATIVES (FOR PRESCREENING) - PHASE 1

Conceptual Alternative	Corresponding Alternative/Plan	Route	Size 3 (10 DWT)	Rise (WL - ft)	No. of Lifts	No. of Lanes	Estimated Model Runs
A. High-Rise Lock Canal	1 Plan synthesizing the following alternatives: 1-d Third Locks Plan 1-e Terminal Lake Plan 1-f Deep Draft Locks	15 + Third Locks Route	100 150 250	90/85 use 90	2	2	6 (t_3 and t_7) See Note
B. Low-Rise Lock Canal	1-g Panamanian Alternative	15 + Third Locks Route	100 150 250	55/30 use 55	1	2	6 (t_3 and t_7)
C. Route 10 Sea-Level Canal or 14S Sea-Level Canal	II- IOCS Route 10 or IOCS Route 14S w/o Tide Gates (IIa) and with Tide Gates (IIb) II-C Vergara Proposal	10, or 14S	150 250 300	0	0	1 2 [50%-1] [50%-2]	24 (t_3 and t_7)
D. Status Quo [Baseline]	1-b Status Quo	15	65	85	3	2	2 (t_3 and t_7)

Notes: t_3=year 2020; t_7=year 2060

- a third set of locks with a lake elevation of 85 feet and single-lift locks for maximum ships of 100,000 DWT.

When it became apparent from early runs of WAM that a single-lane Sea-Level Canal, operated independently, would have insufficient capacity for the target horizon (year 2060), two single-lane Sea-Level Canal cases with tide gates for 150,000 and 250,000 DWT maximum ship sizes, and one with locks, were then evaluated in combination with the Status Quo Canal.

In summation, the purpose of Phase 1 of the Operating Characteristics and Capacity Evaluation Study was to determine for each of approximately 25 alternatives the following operating characteristics:

- transit time of vessels and transit delays at two or three levels of traffic; and,

- capacities of alternative plans for a new or modified canal (developed in terms of acceptable delay time).

The capacities were among the parameters evaluated by SINBOL and CAS in selecting the alternatives for more detailed study.

In addition, for the Sea-Level Canal alternatives, the hydraulics of tides and fresh water inflows, as they affect navigation, and means of ameliorating currents produced by differences in tides between the Pacific and Atlantic ends of the canal, were evaluated.

During Phase 1, therefore, the following specific tasks were accomplished:

- field measurements of lockages, collection and review of data on vessel transits and other data collection and review of past reports;

- review of current Panama Canal operations;

- assessment of operating parameters and indices;

- review of traffic projections;

- review of tidal hydraulics and currents in a Sea-Level Canal using the LATIS model;

- review of the navigation requirements of large ships in a Sea-Level Canal;

- adaptation of the Waterway Analysis Model to suit Panama Canal conditions;

- selection of canal alternatives to be evaluated and establishment of their operating parameters;

- evaluation of transit delays by means of the Waterway Analysis Model, the development of delay/capacity curves and estimation of capacities for the alternative canal cases; and,

- formulation of conclusions regarding capacity and safe navigation.

The vessel mixes and traffic levels were based on the forecasts prepared under the Commodity and Traffic Projection Study by the WEFA Group.

Data on gate operating times and other engineering matters were furnished under the Engineering Study prepared by Yachiyo Engineering Co., Inc. (YEC).

The Final Report on Phase 1 was prepared in July 1992.

OCCE - PHASE 2

Under OCCE Phase 2 capacities of selected study cases (Table 1-2) were evaluated utilizing a refined WAM. Schematics of the alternative plans are shown in Figures 1-2 and 1-3. All of the cases involve the continued use of the existing locks; the sea-level canal would be used in conjunction with the status quo canal.

To expedite the Phase 2 OCCE study, CAS directed TAMS to proceed with the data outputs of Phase 1 of the Commodity and Traffic Projections Study and to estimate a ship mix for a maximum ship of 200,000 DWT from the above output.

During Phase 2, the project proceeded in the following major areas:

- additional data collection and analysis on the existing canal:

  - analysis of arrival patterns of transit ships,

  - analysis of preparation times and underway times for transit vessels,

  - analysis of ship travel times;

- hydrodynamic analysis of maximum allowable vessel speeds, minimum spacing of ships and stopping distance and requirements for tug assistance;

- refinement of the Waterway Analysis Model and running the model for the Phase 2 alternatives;

- estimation of the capacities of Phase 2 alternatives;
- analysis of ship-generated waves for the Sea-Level Canal;
- adaptation of the Routes Model, preparation of data inputs to the model; and running both the Routes and Beaches Models for estimating sediment transport;
- evaluation of minimum lock chamber sizes needed for the alternative design ships;
- preparation of conceptual plans and estimates of costs for navigation support systems;
- evaluation of possible measures to reduce preparation time for transit.

TABLE 1-2
PHASE 2 SIMULATION CASES

Study Case No.	Conceptual Alternative	Maximum Ship Size 000 DWT	No. of New Lanes		Remarks
			Channel	Lock	
1 1a	Status Quo (S.Q.)	65	-	-	For two different ship size distributions
2-3	High-Rise Locks (85ft)	150	2	1 & 2	
4-5	High-Rise Locks (85ft)	200	2	1 & 2	
6	High-Rise Locks (85ft)	150	2	1	Culebra Cut single-lane
7	High-Rise Locks (85ft)	200	2	1	Culebra Cut single-lane
8	Route 10, Tide Gates	250	1	*	Half-tide operations, 40 km single-lane at Pacific side
9	Route 10, Pacific Locks	250	1	3	
9a	Route 10, Pacific Locks	250	1	3	2 Locks in Tandem
10	Route 10, Pacific Locks	250	1	4	

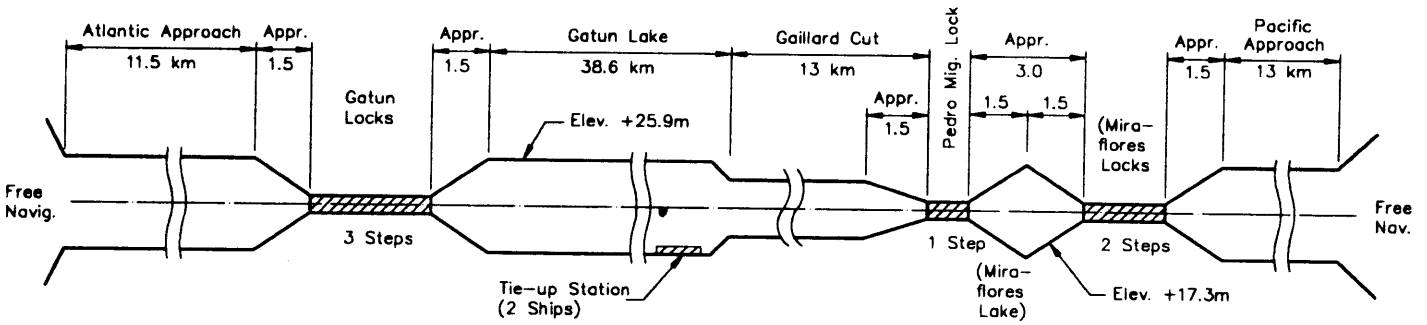
* Tide Gates

During the course of the work, CAS requested that the capacities of the following additional alternatives be estimated.

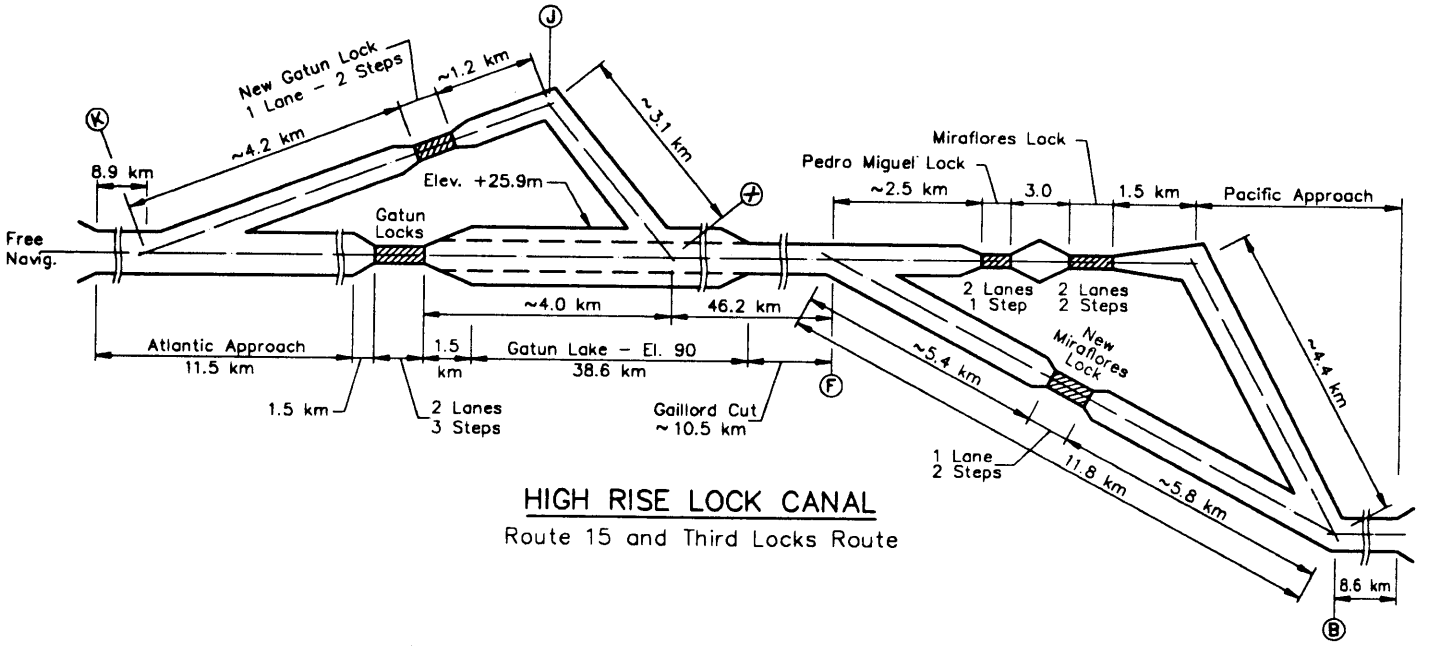
8a Same as Case 8, except that a single lane channel (rather than two lanes) would be used from the Atlantic end to the north tide gate.

9b Same as 9, except that only a single chamber lock (rather than three) would be used at the Pacific end.

SCHEMATICS OF ALTERNATIVE LOCK PLANS



EXISTING PANAMA CANAL (ROUTE 15)



HIGH RISE LOCK CANAL

Route 15 and Third Locks Route

FIGURE 1-2

SCHEMATICS OF ALTERNATIVE SEA LEVEL PLANS

ROUTE 10

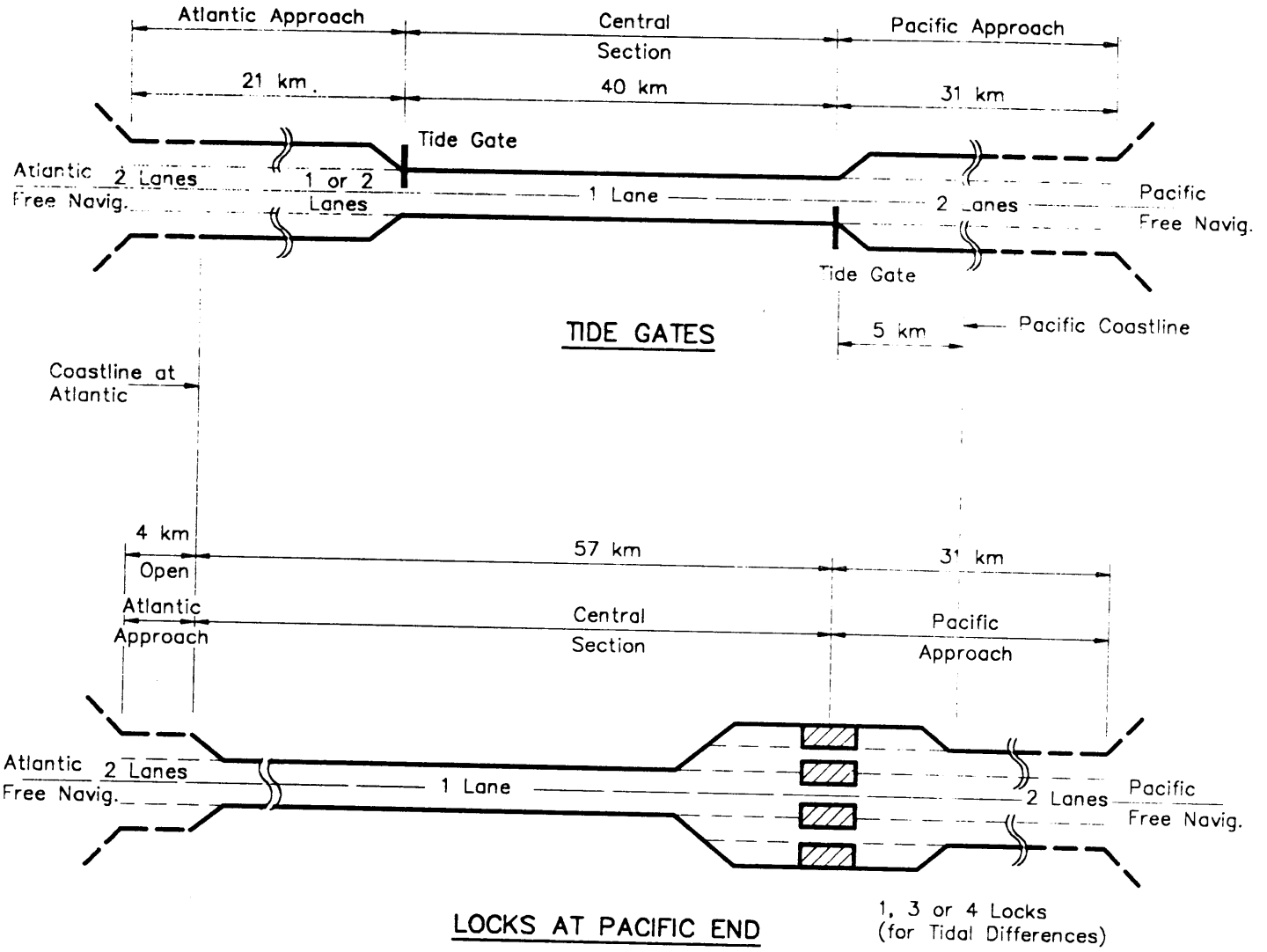


FIGURE 1-3

CHAPTER 2

PANAMA CANAL OPERATIONS/OPERATING INDICES

The following information on existing canal operations is based on discussions with Panama Canal pilots, operating personnel at the locks and key staff of the Marine Transportation and Lock Divisions of the PCC; observations of TAMS and ORNL personnel during transits of the canal and visits to the locks in August, September and October, 1991; and review of the 'Handbook of Lockage Procedure', Revised Edition, 1988 and sections of the Marine Bureau Operations Manual.

A vessel that is bound for the Atlantic from the Pacific side, picks up one or more Panama Canal Commission (PCC) pilots at Balboa, commencing the Panama Canal transit, and enters the Miraflores Lock. As the bow of the vessel approaches the center wall of the locks (consisting of two lanes and two chambers in each lane), wires are fastened to the locomotives that assist in centering the vessel in the transit through the locks. The vessel is raised to elevation of +16.8m (+55 feet) in two lifts, and upon leaving the 2nd chamber, the vessel then travels across Miraflores Lake to the Pedro Miguel Locks.

A similar operation passes the vessel through the single chamber, of a two-lane lockage system, raising it to +25.9m (+85 feet) and leading to the narrowest portion of the canal passage, the Culebra[1] Cut. Travel through the cut for large ships (beams wider than 27½m (90 feet), and ships handling hazardous cargoes, is limited to daylight hours, with single direction sailing for the larger vessels, while smaller vessels are allowed to travel 24 hours a day, in either direction simultaneously.

The Cut ends at the town of Gamboa, following which the vessel travels across Gatun Lake, where travel is unrestricted, and enters the triple chamber, two-lane lockage system, the Gatun Locks which lowers the ship to sea level. After this final section, the pilots are dropped off before leaving Cristobal, the port on the Atlantic end of the canal, effectively terminating the Panama Canal transit.

Vessels transiting towards the Pacific side from the Atlantic follow similar operations, in reverse order.

OPERATIONAL CRITERIA

The principal criteria influencing Canal operations are:

---

[1] Also called the Gaillard Cut

- Safety: Safety of operations is foremost, and is the basis for many of the key operating rules.

- Capacity: The capacity requirement is considered satisfied if ships' times in canal waters do not exceed 24 hours.

- Operating Costs: If the capacity criterion is satisfied, the Canal is operated as economically as possible. If, however, there is impending congestion as a result of a greater than ordinary number of ship arrivals or a lock lane out-of-service, faster but more costly operations will be used such as 'relay' operations (described below) at Gatun and Miraflores Locks.

- Water Use: The availability of water for lockages is not a problem generally and not at all during rainy seasons. During a recent dry season, however, it was necessary to restrict vessel drafts below normal. At such time, water conservation takes on more importance.

OPERATING PROCEDURES

First Come, First Served

The general operating procedure is "first come, first served".

This procedure is modified, however, by various constraints and conditions, such as those that apply to the navigation of large ships.

Clear-Cut Ships

For safety reasons, large ships (27.5m beam and larger) and ships carrying hazardous cargoes (referred to as clear-cut ships) are not permitted to navigate through the Culebra Cut at night and are not permitted to pass or overtake in the Cut.

Accordingly, the practice is to form convoys of clear-cut ships that arrive overnight at each end of the canal. At daybreak, these ships start to move through from each end of the canal using both lanes of the locks in the same direction (i.e., both lanes of the Miraflores and Pedro Miguel locks operate northbound and both lanes of Gatun southbound). The northbound ships then proceed through the Gaillard Cut, operated as a single lane channel and, in Gatun Lake, pass the southbound convoy which, in the meantime, has locked through Gatun. The southbound convoy then proceeds through the Cut in a single lane.

Relay Operations - Multi-Stage Locks

Under normal operations at the multi-stage locks, a team comprising a crew and a set of mules (six or eight for large ships), will pick up a ship as it enters the lock and assist it in locking through the entire complex. A following ship cannot enter the same lane of the lock until the ship preceding it has locked through completely and the team returns to the starting point (10 minutes at Miraflores and 15 minutes at Gatun for mule travel time from one end of the lock complex to the other).

Under relay operations, a second team exchanges with the first at an intermediate point in the lockage (e.g. to middle lock at Gatun) to assist the first ship through the remainder of the lockage and allow the first team to return to pick up a following ship. In this manner the second ship may start locking through the same lane of a multi-stage lock before the first ship completes its lockage, thereby increasing lock capacity.

Relay operations are not normally used because of the costs of the additional crews and equipment involved. There are also practical limits on the number of locomotives that can be maintained in service for extended periods.

Relay operations are used for one lane of a lock only and usually for one shift of eight hours.

Other Operating Procedures

- Passage through the canal can be reserved through a booking system for an additional fee--passage within 18 hours is guaranteed on this basis.

- Preference transits proceed through the Canal upon arrival--e.g. Passenger Ships.

- During light traffic periods, such as for eight hours each night, one lane at Pedro Miguel locks is shut down.

- Small ships can share a lock chamber when their combined lengths do not exceed 800 feet; this is called 'tandem lockage'.

- If only one lane of a lock is being used, both the side wall and center wall culverts are assigned to that lane.

- If an upbound and a downbound passage are proceeding simultaneously through a lock, the center wall culvert is assigned to the upbound lane.

- A ship may tie up on either side or either end of the center wall of a lock, if its passage is delayed.

OPERATING INDICES AND PARAMETERS

The principal challenge in estimating the capacity of the alternative conceptual plans for the Panama Canal is to translate knowledge of how the present canal operates, and the design features and assumed operating characteristics of the alternative plans, into numerical values which can be used with confidence in the estimation process. In this study, the estimation method centers around use of a waterway navigation computer simulation model. Thus, consideration of appropriate parameters and indices of canal operation must start with knowledge of the model's input data requirements and the sensitivity of the model's outputs to changes in the inputs.

The simulation model output that had the largest effect on judgments about the feasibility of any conceptual plan is the average delay incurred by vessels in transiting the canal.

For those conceptual plans which include lock facilities, the variables that have the greatest impact on average delay are the vessel arrival rate and the average lock service time. The vessel arrival rate is a function of the vessel traffic forecast, which was prepared under the Commodity and Traffic Projections Study. From these projections, lists were prepared using a Poisson distribution to generate ship arrival times. Within this study, attention was focused on obtaining and understanding data on lock operations. The mean locking time has the largest impact on average vessel delay. Queuing theory, and experience in analyzing other locking systems, indicate that the variance in locking time also influences delay, but not as significantly. Consequently, the main emphasis of the data analysis was on obtaining representative statistical distributions of lock processing time under different conditions, such as regular versus relay lockage procedure.

Vessels also incur delay at channel sections where navigation is restricted, such as the Culebra Cut.

Most of the simulated transit time in the model occurs in unrestricted navigation channels. Model inputs that affect this output are vessel dimensions (length, beam, draft, block coefficient) and horsepower and the average depth of the channel. These variables jointly determine the model's estimate of vessel speed. As long as the predicted speeds are correct on a relative basis, i.e., in comparing one class of vessels with another, the arrival pattern of the vessels at the locks and restricted channels will be correct. There were sufficient data on vessel characteristics within the Panama Canal Commission's Ship Data Bank to estimate the required inputs with an acceptable level of accuracy.

Operations in a sea-level canal are greatly affected by the tidal currents that might be encountered. Consequently, hydraulic modeling was conducted to determine the potential magnitude of such currents, and to assess the need for positive means of control. It became obvious early in the hydraulic modeling that tide gates or locks would be needed to provide safe navigation conditions. With this type of system, the critical operating parameters are the length of canal between the tide gates, the number of lanes provided, the operating cycle, average ship spacing, and average vessel speed. The relationships among these variables were explored and the outcome of this analysis was the basis for the values that were tested in the simulations.

An important design parameter is the maximum size of ship that will utilize any part of the system. The conceptual plans and vessel traffic forecasts are keyed around a set of maximum size design ships that are anticipated to use the Panama Canal in the future. In some cases, certain classes of vessels, such as the current Panamax vessels, could use efficiently either the existing canal or new locks or channels that would be available. Consequently, development of operating rules for assigning ships to alternative routes has been an important consideration. Since no such routing rules currently exist, empirical methods of generating acceptable results for screening purposes were used in this study. The results are sensitive to the routing rules in cases where a system is operating with significant congestion.

Key operating parameters that impact on capacity used in the analyses herein are:

- maximum size of vessel to be accommodated, which governs the depth and width of the channel and the size of locks;
- vessel arrival rates;
- one-way or two-way operation and the length of canal over which each pertains;
- for alternatives involving locks, lock service time, such as filling and emptying times, opening and closing times of gates and time for vessels entering and leaving locks for different ratios of vessel beam to lock width;
- operating sequence for multi-step locks, i.e. whether regular or relaying lockage;
- traffic management procedures governing such items as the assignment of ships to alternative routes (e.g. new locks or existing);
- for sea-level canal alternatives, the length of canal between tide gates is important, as is the distance from the Pacific end of the canal to

the tide gate at the Atlantic end, which affects the maximum speed of tidal currents;

- maximum vessel operating speed relative to land, which is governed by the size of the vessel, its horsepower, and the ratio of the cross-sectional area of the canal to the cross-sectional area of the vessel;

- minimum spacing between vessels, which is a function of the size of vessel, its speed and stopping distance;

- basic operating features of tide gates, such as opening and closing times, and points in the tide cycle when gates can be operated;

- length of operating cycles for sea-level canal alternatives: i.e., at half-tide intervals (6¼ hours), or full-tide intervals (12½ hours).

Average vessel delay is the index of operating performance that was used in this study to examine the relative capacities of the alternative conceptual plans.

CHAPTER 3

ANALYSIS OF VESSEL ARRIVAL, PREPARATION AND TRAVEL TIME

Two principal types of data compiled by the Panama Canal Commission (PCC) used in connection with the Waterway Analysis Model are: vessel transit times and vessel delays. Detailed historic data on vessel transit times are compiled by the Marine Bureau and kept on file in the Ship Data Bank (SDB) by Management Information Systems. The SDB proved to be a major source of information on vessel transit times for this study. Records of the incidences and causes of delays are compiled by the Locks Division of the PCC.

In addition to the PCC data sources identified above, a review was made of sample data on vessel transits furnished by the PCC early in the study process, and observations were made by TAMS/ORNL personnel during two visits to each of the three existing Panama Canal locks during September and October, 1991. The results of these reviews and the on-site data collection are presented herein.

ANALYSIS OF VESSEL TRANSIT TIMES (PCC SAMPLE DATA)

The Data

Sample data were made available initially by the PCC consisting of timings of 214 vessels (of varying sizes) while they transited the different sections of the canal in both directions over a 6-day period during September, 1991. The data include 32 tandem operations involving 67 ships, i.e. the combination of 2 (in three cases, 3) vessels in a single lockage operation. This type of operation is accomplished with small vessels that arrive at the locks at about the same time.

The times are the actual times it took the vessels to complete the transit, including delays due to fog, locomotive breakdowns, machinery failures, etc.. There are certain instances of errors in the recording process, and in certain other cases the transit data are incomplete. The omissions and errors were addressed in computing the average values and standard deviations of the vessel passage times.

The Analysis

The data were recorded in two main categories: by direction (northbound and southbound), and by beam of the vessel (six widths) (Table A-1). Tandem operations were analyzed separately, only on the basis of direction. The total transit time comprises the following elements shown graphically in Figure 3-1.

EXISTING PANAMA CANAL
DEFINITION OF ELEMENTS OF TRANSIT TIME
(see pages 3-3 and 3-4)

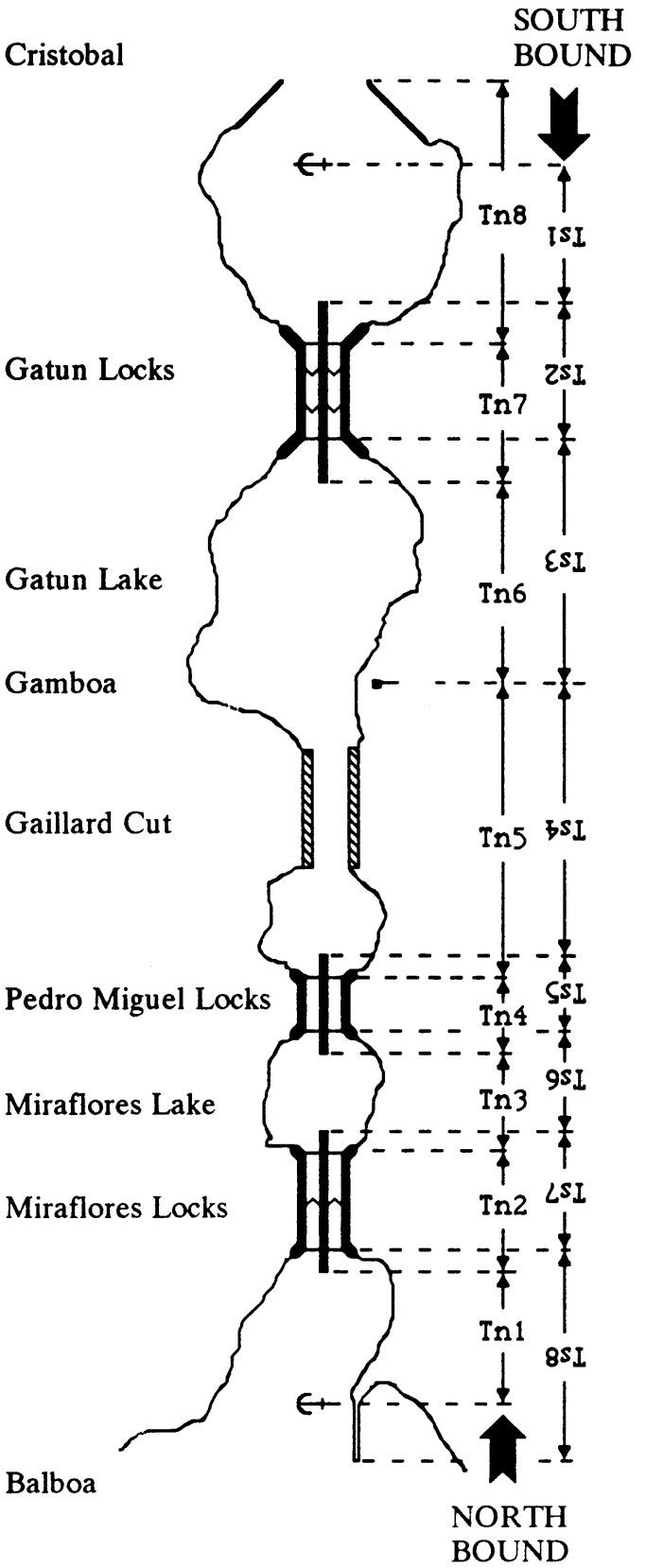


FIGURE 3-1

NORTHBOUND TRANSIT TIME ELEMENTS

Element	Description of Sector		Computational Method
Tn1	Balboa anchorage to Miraflores Lock	=	(Arr. at center wall, MF[1] Lock) - (Dep. anchorage, Balboa)
Tn2	Miraflores Lockage	=	(Clear last chamber, MF Lock) - (Arr. at center wall, MF Lock)
Tn3	Miraflores Lake	=	(Arr. at center wall, PM[2] Lock) - (Clear last chamber, MF Lock)
Tn4(a)	Approach time, PM Lock	=	(Entering time PM Lock) - (Arr. at center wall, PM Lock)
Tn4(b)	Chamber time, PM Lock	=	(Clear chamber, PM Lock) - (Entering time, PM Lock)
Tn4	Pedro Miguel Lockage	=	Tn4(a) + Tn4(b)
Tn5	Culebra Cut	=	(Pass Gamboa) - (Clear chamber, PM Lock)
Tn6	Gatun Lake	=	(Arr. at center wall, G[3] Lock) - (Pass Gamboa)
Tn7	Gatun Lock	=	(Clear last chamber, G Lock) - (Arr. at center wall, G Lock)
Tn8	Gatun Lock center wall to end transit (pass Cristobal)	=	(Pass breakwater at Cristobal) - (Clear last chamber, G Lock)

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[1] Miraflores

[2] Pedro Miguel

[3] Gatun

SOUTHBOUND TRANSIT TIME ELEMENTS

Element	Description of Sector		Computational Method
Ts1	Cristobal anchorage to Gatun Lock	=	(Arr. at center wall, G Lock) - (Dep. anchorage, Cristobal)
Ts2	Gatun Lockage	=	(Clear last chamber, G Lock) - (Arr. at center wall, G Lock)
Ts3	Gatun Lake	=	(Pass Gamboa) - (Clear last chamber, G Lock)
Ts4	Culebra Cut	=	(Arr. at center wall, PM Lock) - (Pass Gamboa)
Ts5(a)	Approach time, PM Lock	=	(Entering time PM Lock) - (Arr. at center wall, PM Lock)
Ts5(b)	Chamber time, PM Lock	=	(Clear chamber, PM Lock) - (Entering time, PM Lock)
Ts5	Pedro Miguel Lockage	=	Ts5(a) + Ts5(b)
Ts6	Miraflores Lake	=	(Arr. at center wall, MF Lock) - (Clear last chamber, PM Lock)
Ts7	Miraflores Lockage	=	(Clear last chamber, MF Lock) - (Arr. at center wall, MF Lock)
Ts8	Miraflores Lock, center wall to end transit (pass Balboa)	=	(Pass breakwater at Balboa) - (Clear last chamber, MF Lock)

The sample timing data at Pedro Miguel Lock is more detailed because daily lockage logs were available, whereas data for the other lock sites were taken from a more generalized daily system transit log.

Values for Tn1, Tn8, Ts1 and Ts8 in the transit timing tables were not computed because the time of ship departures from either end (anchorages at Cristobal and Balboa) and the completion of transits were not available.

The averages computed were then compared to values (referred to as "standard") used by the PCC Marine Bureau to develop ship transit schedules, as shown in Table 3-1.

TABLE 3-1
AVERAGE VESSEL TRANSIT TIMES
(By Vessel Beam)

SOUTH BOUND - AVERAGES

Vessel Size	Sample Size	Cristobal - Locks	Gatun Locks		Gatun Lake		Gaillard Cut		Pedro Miguel		Miraflores Lake		Miraflores Locks		Locks - Balboa
			Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	
		Ts1	Ts2		Ts3		Ts4		Ts5		Ts6		Ts7		Ts8
0 to 60	7	-	1:12	1:00	6:31	-	1:12	-	0:47	0:30	0:15	0:20	0:40	0:40	-
60 to 69	3	-	1:32	1:00	1:36	-	1:14	-	0:38	0:30	0:15	0:25	0:45	0:40	-
70 to 79	15	-	1:11	1:00	3:26	-	1:08	-	0:41	0:30	0:23	0:25	0:45	0:45	-
80 to 89	10	-	1:13	1:10	4:39	-	1:10	-	0:49	0:40	0:20	0:25	0:52	0:50	-
90 to 99	7	-	1:38	1:15	4:33	-	1:22	-	1:02	0:45	0:35	0:30	1:20	1:05	-
100 - over	25	-	1:42	1:45	3:17	-	1:14	-	0:54	1:00	0:29	0:30	1:11	1:10	-
Tandem	14	-	1:16	1:10	-	-	-	-	0:47	0:40	-	-	0:51	0:50	-

NORTH BOUND - AVERAGES

Vessel Size	Sample Size	Balboa - Locks	Miraflores Locks		Miraflores Lake		Pedro Miguel		Gaillard Cut		Gatun Lake		Gatun Locks		Locks - Cristobal
			Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	
		Tn1	Tn2		Tn3		Tn4		Tn5		Tn6		Tn7		Tn8
0 to 60	7	-	0:51	0:40	0:23	0:20	0:41	0:30	1:20	-	3:33	-	1:08	1:00	-
60 to 69	7	-	0:46	0:40	0:23	0:25	0:40	0:30	2:00	-	3:15	-	1:19	1:00	-
70 to 79	17	-	0:49	0:45	0:23	0:25	0:45	0:30	1:27	-	5:40	-	1:20	1:00	-
80 to 89	9	-	1:01	0:50	0:33	0:25	0:50	0:40	1:20	-	4:05	-	1:28	1:10	-
90 to 99	15	-	0:59	1:05	0:26	0:30	0:58	0:45	1:12	-	4:17	-	1:31	1:15	-
100 - over	25	-	1:06	1:10	0:29	0:30	0:55	1:00	1:06	-	4:09	-	1:39	1:45	-
Tandem	18	-	0:49	0:50	-	-	0:37	0:40	-	-	-	-	1:19	1:10	-

COMBINED - AVERAGES

Vessel Size	Sample Size	Miraflores Locks		Miraflores Lake		Pedro Miguel		Gaillard Cut		Gatun Lake		Gatun Locks	
		Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard	Observed	Standard
		T2		T3		T4		T5		T6		T7	
0 to 60	14	0:46	0:40	0:19	0:20	0:44	0:30	1:16	-	4:55	-	1:10	1:00
60 to 69	10	0:47	0:40	0:21	0:25	0:40	0:30	1:46	-	2:46	-	1:23	1:00
70 to 79	32	0:47	0:45	0:23	0:25	0:43	0:30	1:18	-	4:35	-	1:15	1:00
80 to 89	19	0:56	0:50	0:26	0:25	0:50	0:40	1:15	-	4:25	-	1:20	1:10
90 to 99	22	1:06	1:05	0:29	0:30	0:59	0:45	1:15	-	4:22	-	1:33	1:15
100 - over	50	1:09	1:10	0:29	0:30	0:55	1:00	1:10	-	3:43	-	1:40	1:45
Tandem	32	0:50	0:50	-	-	0:41	0:40	-	-	-	-	1:17	1:10

COMBINED - STANDARD DEVIATIONS

Vessel Size	T2	T3	T4	T5	T6	T7
0 to 60	0:13	0:14	0:24	0:47	3:59	0:10
60 to 69	0:03	0:09	0:07	2:00	1:11	0:22
70 to 79	0:05	0:14	0:13	0:54	4:28	0:17
80 to 89	0:13	0:15	0:19	0:56	2:55	0:18
90 to 99	0:19	0:16	0:25	0:31	2:32	0:18
100 - over	0:16	0:14	0:16	0:15	2:11	0:20
Tandem	0:11	0:16	0:15	0:15	1:18	0:16

Notes:

1) 23:31 — Timing not considered in computations, error in recording

2) [illegible] — Instance where arrival of locomotive (to assist vessel into the locks) occured after vessel's arrival at center wall, at the Pedro Miguel locks

3) Zodiac, Frio Espana — Tandem operation involving the two ships grouped by the dotted pattern (to differentiate the next tandem operation, the dotted pattern was omitted)

4) Tn1, Tn8 / Ts1, Ts8 — These values are not computed as departure timings from either anchorages, and arrival timings at either ends are not available

Observations Regarding the Data

1. In nearly all the categories, and in both directions, "observed" lockage times were equal to or higher than the standard times.

2. The standard deviations are noticeably higher for transit times at the Culebra Cut and Gatun Lake than elsewhere in the canal.

3. In cases that involved the accompaniment of PCC tug boats along with the vessel, lockage times were slightly higher.

ANALYSIS OF PANAMA CANAL LOCKAGE DATA COLLECTED DURING FIELD OBSERVATIONS

Observations were made at each of the three locks on the Panama Canal. The following data were collected: Ship size (length, beam, and draft), direction (northbound and southbound), lane (east and west), and transit time (approach, entry, chamber, and exit). Two lock operating procedures were observed: regular and relay lockage. Relay lockage expedites ship movements through multi-chamber locks by using two sets of locomotives and crews in guiding ships between the different chambers. A crew and set of locomotives that starts a ship's lockage, relays the ship to a second crew to complete the lockage, while they return to the starting point to pick up a second ship. The regular lockage method utilizes a single set of locomotives and crew all the way through. These operations were described in more detail in Chapter 2.

Two days were spent at each lock and the number of ships observed at each lock were as follows:

Lock Name	Number
Miraflores	23
Pedro Miguel	18
Gatun	12

The limiting dimensions for a ship transiting the Panama Canal are:

Beam:	32.3 m (106 feet)
Length:	294 m (965 feet)
Draft:	12.0 m (39.5 feet)

Beam and draft are the major factors affecting a ship's speed of movement through the canal. The wider the beam and deeper the draft, the slower the ship is able to move through the locks.

Table A-2 provides the observed transit time data for each lock. Relay lockage was observed only at Miraflores Lock. Northbound and southbound times and east and west lane times have been combined in the table. This time is divided

into approach, entry, chamber, and exit times. When two or more ships fall into one vessel size category, the average time is calculated for the ships. The PCC standard time is also shown for each category of vessel size.

While this sample is small, some general observations can be made. No consistent pattern of lockage time differences can be found between the observed regular lockage transit times and standard time compiled by the PCC. Four relay operation observations were made at the Miraflores Lock. In each case, the time was higher than the standard PCC time.

Chambering time usually took the most time of the four categories (approach, entry, chamber, and exit). This time obviously increases as the number of chambers in each lane at the lock increases. Pedro Miguel has one chamber, Miraflores has two, and Gatun has three in each lane.

ANALYSIS OF PCC SHIP DATA BANK RECORDS

The PCC provided Ship Data Bank (SDB) records for all vessel transits in calendar year 1990. Data for 13,611 transits were provided, split into a vessel characteristics file and a vessel transit file. Table A-3, prepared by the PCC, provides information on the variables and the record layouts for these two files. Only eight (8) records had to be deleted due to faulty data entry, leaving 13,603 transit records available for analysis.

The SDB records were analyzed to produce the following:

- locking times and transit times by vessel size;
- preparation for transit times;
- vessel arrival patterns and scheduling practices.

All analyses were performed using the SAS statistical analysis package, on a mainframe computer. The results were grouped according to the PCC vessel beam and draft categories, as follows:

Vessel Class	Beam (ft.)	Draft (ft.)
1	<60	-
2	60-69	-
3	70-79	-
4	80-89	<=36
5	80-89	>36
6	90-99	<=30
7	90-99	30-36
8	90-99	>36
9	>99	<=30
10	>99	30-36
11	>99	36-38
12	>99	>38

Locking and Transit Times

The objective of this analysis was to determine the mean, standard deviation, minimum, and maximum values of approach time and lockage time at each lock, by direction (northbound or southbound) and vessel class. Approach time is defined as the vessel's enter time minus its arrival time at the lock's center wall, and lockage time is defined as clear time minus enter time. Thus, lockage time here includes the entry and exit operations, which were later separated for the model input. Transit time parameters, defined as the difference between transit termination time and transit underway time, were also computed.

Table A-4 presents the results of the locking time analysis. As expected, both the approach time and the lockage time increase as vessel size increases, although the rate of increase is irregular. There is a noticeable, and usually consistent, difference in the times for the two transit directions, so directional differences were preserved in preparing locking time input distributions for the simulation model. It also appears that the minimum and maximum values are unreliable, and likely reflect data entry errors or some unusual delay conditions. Thus, in developing the simulation model inputs, emphasis was placed on representing the central portions of these locking time distributions, and on smoothing out the transitions from one vessel class to the next.

Table 3-2 presents the transit time results. In all cases northbound transits take longer than southbound transits, resulting, at least in part, from a greater percentage of southbound ships in ballast (although a few of the minimum and maximum times don't follow the average trend). Averaged across vessel classes, transit time was 12.5 hours northbound and 9.8 hours southbound, with a weighted average of 11.3 hours. Given the large maximum times noted, these times obviously include some delay time, despite attempts to screen delay data. For reference, the transit time table used by the PCC for ship scheduling purposes is included as Table 3-3. This table indicates an average transit time of about 8 hours, and matches information obtained during the field data collection in Panama.

Analysis of Preparation for Transit Time

A review of the 1990 Ship Data Bank records indicates that on average, the interval between a vessel's arrival time and underway time is about 11.6 hours. An investigation was made to identify the activities occurring during this interval and any factors causing delay. This was done in order to determine whether any measures could be introduced to reduce the time required for preparation for canal transit.

A detailed examination of SDB records was made, as discussed below. In addition, discussions were held with representatives of the Traffic Management Division of the PCC, APN, ship agents and bunkering firms.

TABLE 3-2
VESSEL TRANSIT TIMES FROM SDB RECORDS

Vessel Class	Dir.	No. Vsl.	Transit Time (minutes)			
			Avg.	SD	Min.	Max.
1	N	1066	628	261	354	2750
	S	1145	530	155	350	1897
2	N	567	744	346	370	3537
	S	547	536	183	362	2795
3	N	1385	785	398	355	4605
	S	1387	547	174	344	2161
4	N	561	773	342	385	2781
	S	534	588	235	393	2960
5	N	40	946	356	525	1684
	S	7	857	727	442	2456
6	N	269	795	293	405	2446
	S	243	623	197	418	1938
7	N	233	830	283	485	1715
	S	286	664	228	456	2272
8	N	134	868	361	532	2684
	S	143	672	220	482	1843
9	N	446	778	280	465	2809
	S	357	633	162	420	2086
10	N	477	741	197	547	1896
	S	381	644	159	463	2378
11	N	0	--	--	--	--
	S	177	642	142	468	1670
12	N	273	798	242	579	2302
	S	661	692	210	511	2086
Total/ Average	N	5451	751 = 12.5 hours			
	S	5868	590 = 9.8 hours			

TABLE 3-3
PCC TRANSIT TIME STANDARDS

Vessel Size Beam (ft)	Miraflores Locks		Miraflores Lake	Pedro Miguel Locks	Gatun Locks		Average Gatun Lake Speed		Cut Running Times	
	Regular	Relay			Regular	Relay	Knots	Time	Northbound	Southbound
Up to 60	40	30	20	30	1:00	30	15	1:30	Ballast 1:00	Under 34' 1:10
60 - 69	40	30	25	30	1:00	35	12	1:45	Under 34' 1:00	34'-36' 1:15
70 - 79	45	35	25	30	1:00	35	10	2:00	34'-36' 1:05	36'-37' 1:20
80 - 89	50	40	25	40	1:10	40	8	2:45	36'-37' 1:10	37'-Up 1:25
80 - 89 36' up	50	40	25	40	1:10	45	7	3:15	37'-up 1:15	
90 - 99	55	40	25	40	1:10	40	6	3:45		
90-99 30' - 36'	1:05	45	30	45	1:15	45	4	5:30		
90 - 99 36' - 39.6'	1:10	50	30	50	1:25	50	600' long or 38' draft avg.10 knots			
100 - Ballast	1:00	45	25	40	1:10	45				
100 30' - 36'	1:10	50	30	50	1:25	50				
100 36' - 38'	1:20	1:00	30	1:00	1:45	1:00				
100 38' & over	1:25	1:00	30	1:00	2:00	1:15				
100 8/16 Deeply laden	1:35	--	30	1:10	2:10	--				
Tandem	50	40	25	40	1:10	40				
	+ 10 if S.W. culvert			+ 10 if S.W. culvert	+ 15 if S.W.	+10 if S.W.				

Three times are recorded by the PCC during preparation for transit: Arrival Time, Ready Time, and Underway Time. Arrival time is reported by signal stations. At the Pacific side, arrival is recorded when a vessel passes the sea buoy. At the Atlantic side, arrival of large ships (supers), 90-ft beam and larger, is recorded at the outer anchorage and arrival of smaller ships is recorded as they pass through the breakwater.

Ships that have transited the Canal previously must only have their papers checked and be cleared by a boarding officer in order to be considered ready for transit, a process that usually takes less than one hour and, in any event, is recorded as a maximum of one hour. Ships which are not able to get underway, because of congestion or unsafe navigation conditions, or because they have not previously transited the Canal, proceed to an anchorage. Some ships, as noted below, go to port before transiting. Ships arriving at the Canal for the first time are subject to admeasure, whereby their pertinent characteristics are checked and recorded permanently in PCC files; this process takes five to six hours.

The above administrative procedures are essential and comprise only a small part of the total interval from arrival to underway time. Any efficiencies that could be achieved in these procedures would have only a minor impact on time in canal waters.

Some ships, upon arrival, elect to go to port to discharge or take on cargo, for repairs or stores. These vessels are considered ready for transit after they complete their business in port and are cleared for transit. Here again, this time contributes to the average interval between arrival and underway times, but, in fact, the activity is at the discretion of the ship, not the Canal, and cannot be considered delay time.

Once ships are cleared for transit (Ready Time), although the typical practice is first come, first served, actual underway time is also influenced by the following factors:

- whether the ship has a priority or preference rating, and
- whether the ship is a super.

Priority passage through the Canal can be reserved for an additional fee, which guarantees passage within 18 hours. This is done typically by vessels providing liner service. Ships for which schedules are critical, e.g. passenger ships, are given a preference rating, which allows them to get underway directly upon being cleared (and there are no impediments to safe navigation).

The above practices result in some shuffling in the order of transits, but do not contribute to average delay time.

Large ships (supers), for safety reasons, are not permitted to navigate through the Culebra Cut at night and periods of dense fog (which occur typically at night during the rainy season), and they may not pass or overtake each other in the Cut (clear cut transits). Accordingly, the practice is to hold and form convoys at each end of the Canal of the large ships that arrive overnight. During the early morning hours the large ships have priority and get underway from both ends of the canal using both lanes of the locks in the same direction (i.e., both lanes of Miraflores and Pedro Miguel operate northbound and both lanes of Gatun operate southbound). The northbound ships pass through the Cut in single file. By the time the last ship of the northbound convoy clears the Cut, the southbound convoy begins to arrive and passes through in single file. Once the southbound convoy clears the Cut, normal operations resume. The interval between arrival and underway times of the supers that arrive overnight may reasonably be considered delay time, inasmuch as the ships are held at anchor, although capacity for transit is available.

Some vessels, learning upon arrival that they will have a lengthy wait before they are allowed to get underway, elect to bunker, take on stores, or make minor repairs, while at anchor. In this case, ready time is set at the completion of these activities, although their place in the transit queue is governed by arrival time and their priority rating. These activities, therefore, do not contribute to delay, the ships merely take advantage of the delay to accomplish other important functions. Some ships elect to lose their place in queue in order to bunker or make minor repairs, but this is not a delay imposed by canal operations.

Arrival, Underway, and Segment Transit Times in Ship Data Bank Records

The statistical distributions of arrival time, ready time, and transit underway times at the Canal are important from a modeling perspective. Simple parameters such as mean and standard deviations of transit times through different segments of the Canal are also useful in simulation modeling. Several time components available in the Ship Data Bank (SDB) were analyzed in detail to obtain the underlying distributions of these variables. Northbound and southbound traffic are treated separately throughout the analysis. Vessel classes shown in Table 3-4, as identified earlier, were used for analyses which require differentiating various vessel types. Also presented in the table are the number of vessels in each class that used the Canal in 1990. Additionally, vessel classes 1 through 5 are classified as *small* vessels, 6 through 12 are classified as *large* vessels and 13 and 14 are classified as *passenger* and *recreational* vessels.

TABLE 3-4
VESSEL CLASSES AND OBSERVED FREQUENCIES (1990)

Vessel Class	Beam (ft)	Draft (ft)	No. of Ships	
			Northbound	Southbound
1	< 60	-	1371	1604
2	60 - 69	-	588	596
3	70 - 79	-	1455	1493
4	80 - 89	<= 36	587	565
5	80 - 89	> 36	40	139
6	90 - 99	<= 30	298	233
7	90 - 99	30 - 36	262	295
8	90 - 99	> 36	149	152
9	> 99	<= 30	493	381
10	> 99	30 - 36	366	384
11	> 99	36 - 38	121	177
12	> 99	> 38	282	670
13	(Passenger)	-	46	97
14	(Recreational)	-	247	393

The purpose of this analysis was to derive the mean values and/or determine the true statistical distributions of the following temporal events while ships are in transit through the Canal:

- Arrival Time (by direction only);
- Transit Underway Time (by direction and vessel class);
- Difference in Ready Time and Arrival Time (differential ready time, DRT: by direction and vessel class);
- Difference in Underway Time and Ready Time (differential underway time, DUT: by direction and vessel class);
- Transit times for vessels of different class (by direction and vessel class).

Transit time through the Canal is divided into the following 5 different segments:

Segment 1: Transit time between Gatun Locks & End of Transit (NB);
Transit time between Transit underway & Gatun Locks (SB);

Segment 2: Transit time between Gatun Locks & Gamboa Passing (NB & SB);

Segment 3: Transit time between Gamboa Passing & Pedro Miguel Locks (NB & SB);

Segment 4: Transit time between Pedro Miguel Locks & Miraflores Locks (NB & SB);

Segment 5: Transit time between Miraflores Locks & End Transit (SB);
Transit time between Transit Underway & Miraflores Locks (NB).

Characteristics of the Ship Data Bank

For each ship that traversed through the Canal the following relevant temporal events are recorded in the ship data bank:

- Arrival time;
- Ready time;
- Underway time;
- Arrival and departure times at three sets of locks; and
- Passing time at Gamboa.

Arrival time, ready time and transit underway time refer to the cumulative elapsed times from a reference point of time, selected to be the hour 00:00 of January 1, 1990. The differences in ready time and arrival time, and transit underway time and ready time, for each ship are absolute time intervals.

The proposed analyses require arrival, ready and underway times of each ship that traversed the Canal throughout 1990. The ship data bank contains information on arrival times for all the ships, but ready times for about 20 ships are missing. This lack of continuity in the data complicates the analysis of the ready times. To solve this problem, erroneous ready times were corrected to read the same as the arrival times, and the faulty underway times were corrected to read the same as ready times. Since the number of missing data points are very few (229 out of 13483 records), this correction did not significantly influence the results of the analysis.

Screening the Data for Outliers

Technically it is possible for a ship to be ready for transit as it arrives. Also, it may be possible for any ship to be underway for transit immediately after it is ready. Thus, the minimum values for DRT and DUT can be zero hours. The scheduling practices at the Canal indicate that a majority of ships are underway for transit within 24 hours of their arrival. In other words, ships with DRT and DUT values higher than 24 hours are abnormally delayed, and should be excluded from analysis of delays due to scheduling practices at the Canal. For these reasons, the data were screened to retain only observations with DRT and DUT values in the range between 0 hours and 24 hours.

Results of preliminary analysis indicated that a sizable number of *outliers* were influencing the mean values of transit times through different segments. Since the purpose of this analysis is to develop data on normal ship speeds, an effort was made to eliminate these outliers. A *reasonable* value for transit time in each of the segments was assumed, based on the field data collected in Panama. Transit time values through a given segment of less than half or more than twice the reasonable value were defined as outliers, and removed from the transit time analysis. Details of this screening process are presented in Table 3-5.

TABLE 3-5
SUMMARY OF SCREENING FOR ELIMINATING OUTLIERS

Variable*	Assumed Avg. Value (hrs)	Min. Value (hrs)	Max. Value (hrs)	Northbound			Southbound		
				Before	After	% Outliers	Before	After	% Outliers
DRT	N/A	0.00	24.0	6,232	5,612	9.9	7,023	6,096	13.2
DUT	N/A	0.00	24.0	6,298	5,713	9.3	7,174	6,189	13.7
T.Seg1.	1.0	0.50	2.0	6,229	5,112	17.9	7,115	6,753	5.1
T.Seg2.	3.0	1.50	6.0	6,186	4,366	29.4	7,108	5,898	17.0
T.Seg3.	1.0-1.5	0.50	3.0	6,210	5,821	6.3	7,072	6,999	1.0
T.Seg4.	0.5	0.25	1.0	6,225	4,813	22.6	7,074	5,264	25.6
T.Seg5.	0.5-1.0	0.25	2.0	6,229	5,497	11.7	7,115	7,061	0.1

* T.SegX. represents Transit time through Segment X.

Analysis of DRT and DUT

As mentioned earlier, several observations in the database indicated ready time ahead of arrival time. For the purpose of analyzing this DRT, these observations were treated as "missing" values. An *analysis of variance* indicated that DRT and DUT are affected by the direction of travel as well as the vessel class. The data were tested for normality using parametric statistical procedures available in SAS. The analysis indicates that DRT and DUT are normally distributed. Mean and standard deviations (along with minimum and maximum values) of DRT and DUT are presented in Tables A-5 and A-6, respectively, by transit direction and vessel type.

The data were also analyzed to see if there is any significant difference in DRT and DUT between the *small* and *large* ships. The results of the analysis of variance are presented in Table 3-6. The results indicate that there is a statistically ($\alpha = 0.05$) significant difference in the DRT and DUT components for small vessels and large vessels. After arrival, smaller ships are readied, on the average, 0.816 and 0.852 hours later than the larger ships for northbound and southbound traffic, respectively. On the other hand, smaller ships are underway for transit faster than the larger

ships. The differences in DRT components for larger ships and smaller ships are 1.213 hrs and 1.359 hrs in the northbound and southbound directions, respectively.

TABLE 3-6
ESTIMATES OF DIFFERENCES IN DRT AND DUT
BETWEEN LARGE AND SMALL VESSELS

Time Component	Northbound Traffic		Southbound Traffic	
	Estimated Difference (hrs) (Large-Small)*	Standard Error of Estimate	Estimated Difference (hrs) (Large-Small)*	Standard Error of Estimate
DRT	-0.8164	0.0661	-0.8524	0.0687
DUT	1.2130	0.0887	1.3590	0.0885

* Negative sign indicates that Smaller ships are delayed longer.

Conclusions Concerning Preparation for Transit Time

In summary, based on review of SDB data and discussions with knowledgeable persons, the principal factor causing delay of ships preparing to transit appears to be the clear cut restriction in navigating the Culebra Cut. Once the Cut is widened and improved, and high mast lighting installed, delays prior to transit will decline significantly. No other measure to reduce preparation for transit time would have significant impact.

Analysis of Data for Transit Times by Segment

For each of the vessel classes, the SDB data were analyzed to derive mean travel time in each of the five segments defined earlier. The data were checked for consistency. No dates are recorded for arrival and departures at locks and Gamboa. The only date recorded after a ship is underway for transit is at the event of departure from the last set of locks. From this, it was expected and observed that the time of transit for the ships varied widely. Most ships (about 99%) completed transit in less than three days. (A few ships took longer than 360 days, providing evidence of recording errors or other anomalies.) Analysis of transit times was performed only for ships that cleared the Canal within three days; if the total transit is recorded as exceeding three days, the record was discarded for analysis.

Since there is no way of knowing the actual arrival/departure times at specified locations (i.e. three sets of locks and Gamboa) which are recorded as 00:00 hours, those observations were discarded. Most importantly, it is assumed that

any segment takes less than two days (i.e. transit through each of the segments takes place within two days from the time of departure from the previous segment). The surviving observations were screened further for outliers, as described earlier. Results of this analysis are shown in Tables A-7 though A-11. These results were used to calibrate the WAM ship speed function and associated adjustment factors.

Arrival and Underway Time Analysis

A principal need for analysis is to determine the probability distributions of ship arrival and underway times, to devise a strategy for introducing vessels into the simulation in a way which replicates either the operation of the current system (for model calibration) or the planned mode of operation of alternative future systems. The SDB records for 1990 were used to conduct the required analyses.

Monthly Arrival Patterns

The percentages of ships arriving in each month in each direction were determined from the SDB data on day of arrival. Separate distributions were developed for small ships (vessel classes 1 through 5) and large ships (vessel classes 6 through 12). The results are shown in Figures 3-2 (Northbound), 3-3 (Southbound), and 3-4 (combined directions). For Northbound transits, the large ships arrived at a higher than average rate in April of 1990, and small ships exhibitewd a similar peak in October. No significant departures from the mean are evident for Southbound ships. Looking at both directions combined, there are no departures from the expected average of 8.33 percent per month that are significant enough to justify using differential ship arrival rates by month or season. Consequently, ship arrival times were assumed to be distributed randomly throughout the year for all subsequent analyses.

Ship Arrival Probability Distribution

In general, the arrivals at a free-flowing section of a waterway can be expected to be random. When random arrivals are observed the counting distribution of arrivals at the section will follow a Poisson process with the following probability density function:

$$P(x) = \frac{(\lambda t)^x e^{-\lambda t}}{x!} \qquad 1$$

where:

$P(x)$	=	probability that x ships will arrive during a counting interval t
λ	=	average rate of arrival, ships/day (flow rate)
t	=	duration of each counting interval, days
λt	=	average number of vehicles during a period of duration t

PERCENT TRANSITS FOR 1990 BY MONTH (NORTHBOUND SHIPS)

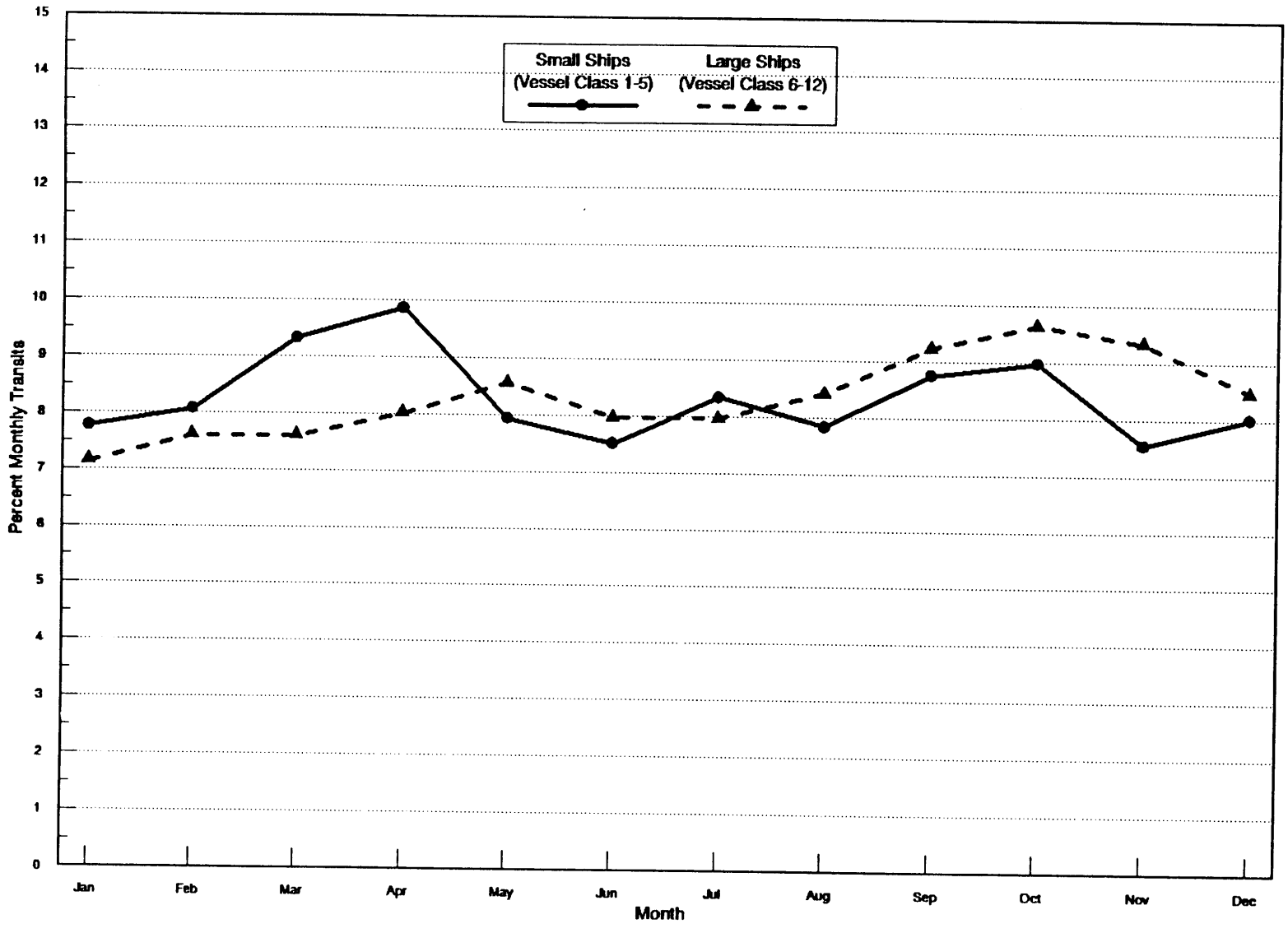


FIGURE 3-2

PERCENT TRANSITS FOR 1990 BY MONTH (SOUTHBOUND SHIPS)

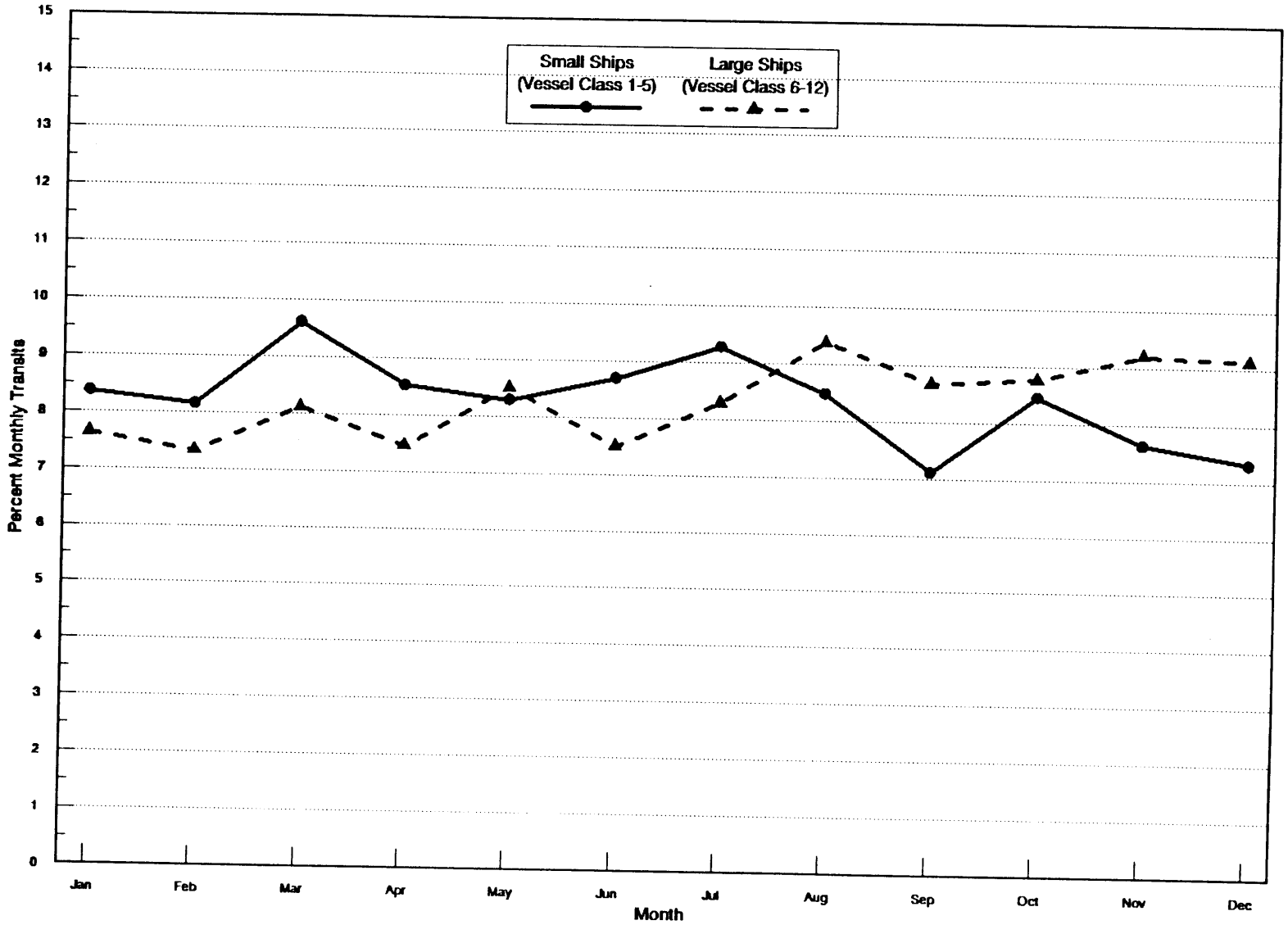


FIGURE 3-3

PERCENT TRANSITS FOR 1990 BY MONTH (BOTH DIRECTIONS)

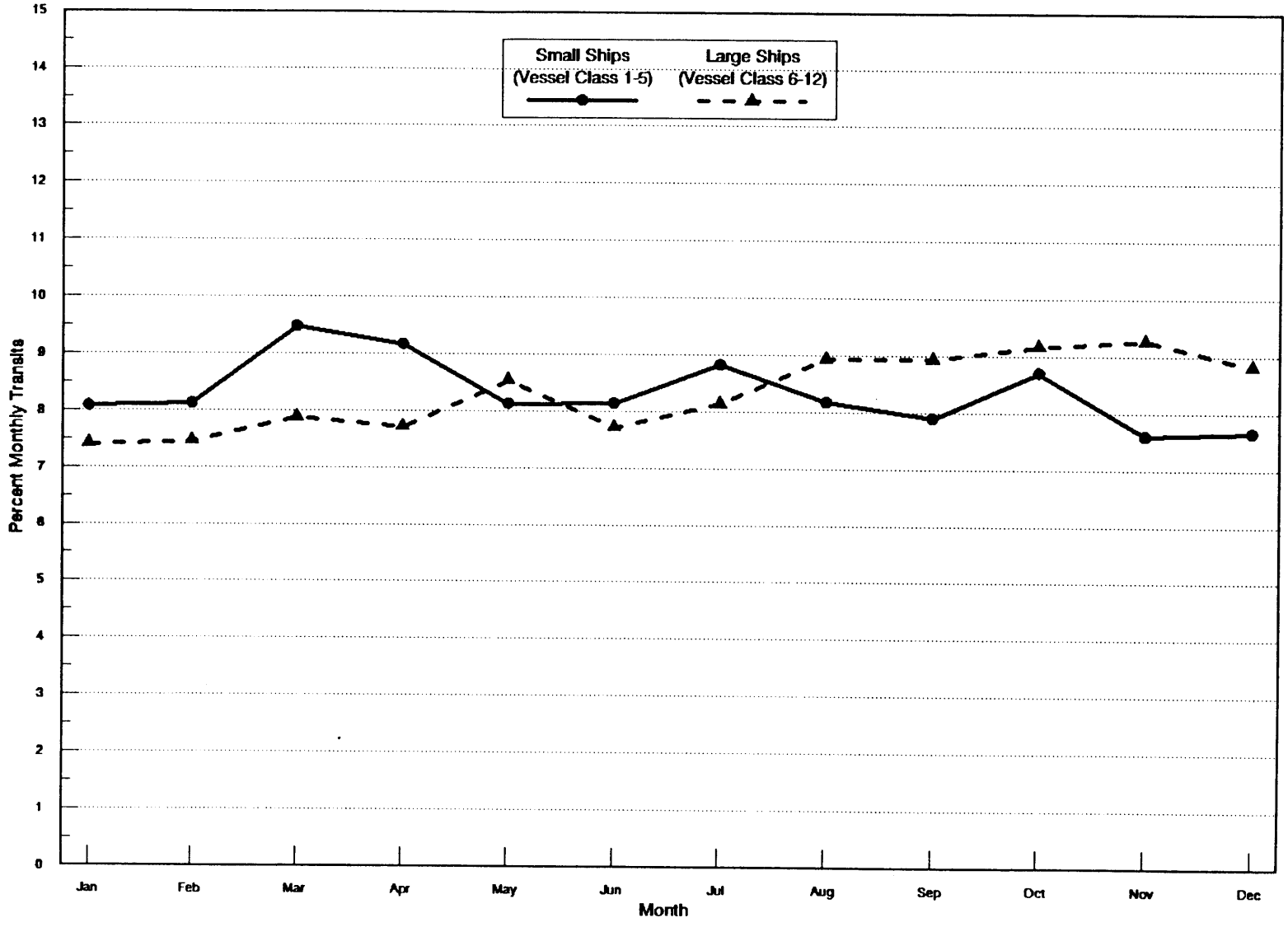


FIGURE 3-4

Under these conditions, the ratio of mean and variance is approximately 1.0. In congested conditions, the flow is more uniform than random. The variance of the number of ships per interval is decreased. Consequently, the ratio of mean and variance is expected to be greater than 1.0. Often times, the normal distribution is also applied to congested flow conditions. For free-flow conditions, as the number of arrivals follows a Poisson process, the interarrival times (time headway between two successive ship arrivals) will follow a negative-exponential distribution. The probability density function of the negative exponential distribution is given by:

$$P(h \geq t) = e^{-\frac{t}{\bar{t}}} \qquad 2$$

where:

$P(h \geq t)$ = probability of the headway h being greater than or equal to the indicated time interval t.

$\bar{t}$ = mean headway between two successive arrivals.

The frequency distribution of specified number of arrivals per day was computed from the ship data bank by transit direction. There are 6,305 northbound and 7,179 southbound ships, with mean headways of 1.388 hours and 1.219 hours in the Northbound and Southbound directions, respectively. The expected arrivals in each headway class (i.e. specified number of arrivals per day) were computed using the negative exponential probability density function (Eq. 2). A χ^2 goodness of fit test was performed to investigate the applicability of the negative exponential distribution to the arrival times of ships. Table 3-7 summarizes the results of this analysis. The computed χ^2 value of the fits indicate very high probabilities (nearly 100%) for Type I error in accepting the hypothesis that the interarrival time headways follow the negative exponential distribution.

Looking at the individual frequency values for the quarter hour increments used in the table, it appears that the directional distributions have the characteristic shape of the negative exponential distribution, but the initial height and rate of fall of the curve are not close enough to theory to survive a statistical test. Dividing the data into more or fewer groups produced similar results. It is likely that a Gamma or some other Erlang type distribution would produce an acceptable fit. It is also possible that the larger ships plan their arrivals to coincide with the current scheduling practices for transit of the Culebra Cut, which produces a departure from purely random arrivals. These findings notwithstanding, it still appears prudent to assume random arrivals as the appropriate basis for simulations of future systems. It is well known that random arrivals place the greatest stress on capacity constrained transportation systems. Consequently, assuming this condition will provide conservative estimates of system capacity.

TABLE 3-7
ANALYSIS OF INTER-ARRIVAL TIMES

Interval (hrs)	Northbound			Southbound		
	f_o	f_t	$(f_o-f_t)^2/f_t$	f_o	f_t	$(f_o-f_t)^2/f_t$
0.00-0.25	1,096	1,039.09	3.12	1,319	1,330.95	0.11
0.25-0.50	840	867.84	0.89	1,071	1,084.20	0.10
0.50-0.75	717	724.82	0.08	937	883.20	3.28
0.75-1.00	591	605.37	0.34	702	719.45	0.42
1.00-1.25	533	505.60	1.48	619	586.07	1.85
1.25-1.50	387	422.27	2.95	429	477.42	4.91
1.50-1.75	361	352.68	0.20	365	388.91	1.47
1.75-2.00	294	294.56	0.00	292	316.80	1.94
2.00-2.25	253	246.01	0.20	255	258.07	0.04
2.25-2.50	174	205.47	4.82	204	210.23	0.18
2.50-2.75	163	171.61	0.43	159	171.25	0.88
2.75-3.00	123	143.33	2.88	148	139.50	0.52
3.00-3.25	118	119.71	0.02	109	113.64	0.19
3.25-3.50	99	99.98	0.01	79	92.57	1.99
3.50-3.75	86	83.50	0.07	79	75.41	0.17
3.75-4.00	56	69.74	2.71	71	61.43	1.49
4.00-4.25	69	58.25	1.99	44	50.04	0.73
4.25-4.50	48	48.65	0.01	57	40.76	6.47
4.50-4.75	52	40.63	3.18	41	33.21	1.83
4.75-5.00	34	33.93	0.00	26	27.05	0.04
5.00-5.25	31	28.34	0.25	25	22.03	0.40
5.25-5.50	29	23.67	1.20	24	17.95	2.04
5.50-5.75	23	19.77	0.53	21	14.62	2.78
5.75-6.00	20	16.51	0.74	21	11.91	6.94
>=6.00	108	83.68	7.07	79	52.33	13.59
Mean Headway		1.388 hrs			1.219 hrs	
Standard Deviation		1.467 hrs			1.307 hrs	
Degrees of Freedom		24			24	
X^2		35.170			54.362	
Prob. of Type I Error		0.946			0.999	

Ship Generation and Scheduling

The SDB records were used both to prepare a list of ship arrivals in 1990, for use in model calibration simulation runs, and to analyze the actual pattern of scheduled ship underway times in 1990, for use in developing ship scheduling procedures for those future system alternatives requiring continuation of current scheduling practices.

Ship List for 1990

All 13,603 valid vessel transit records were used to create a time ordered list of vessel traffic for input to the model. Each record in the list specifies the vessel underway time, vessel class, commodity carried, net cargo tons, laden or ballast, and travel direction. Underway times were selected to remove the influence of the activities occuring between the vessel's arrival and its beginning of transit, since these activities are not included in the simulation model. Also, the underway time captures any effects of the vessel scheduling practices (discussed below). The vessel classes used are the 12 classes based on beam and draft as defined above, with the addition of classes 13 and 14 for passenger vessels and recreational craft, respectively. The commodity code was used to preserve the PCC vessel type code, for possible cross reference purposes. Laden or ballast condition was estimated by comparing the vessel's transit draft with its maximum draft.

Ship Scheduling

The analysis of ship underway times in the SDB records indicated that the ship underway events are **not** random, that is, the time intervals between successive ships in one direction do **not** follow the negative exponential distribution. The scheduling practices used significantly influence the transit underway times of the ships. Another possibly important consideration for scheduling is the presence of fog. Large ships are normally not allowed to pass through the canal during night hours, and night traffic through the Culebra Cut is also sometimes restricted during the rainy (foggy) season.

The SDB records were analyzed to test the influence of ship size and season on ship underway times. Figures 3-5 and 3-6 depict the patterns of underway times of small and large ships during different seasons for Northbound and Southbound ships, respectively. In these figures, large ships are those with beam exceeding 27.4 meters. It can be seen that the scheduling practices discussed above are reflected in these figures. The seasonal effect is also noticeable, particularly for the night hours, but it does not distort the basic pattern of ship underway times. Consequently, it was determined that there was no need to use different hourly ship underway time patterns for the different seasons.

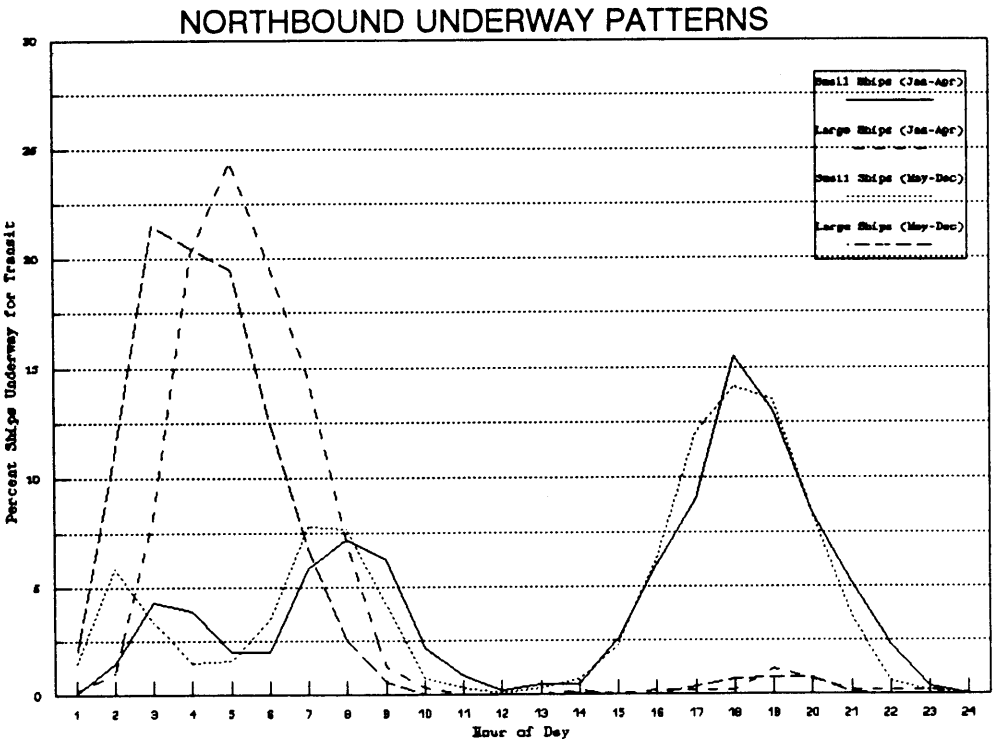


FIGURE 3-5

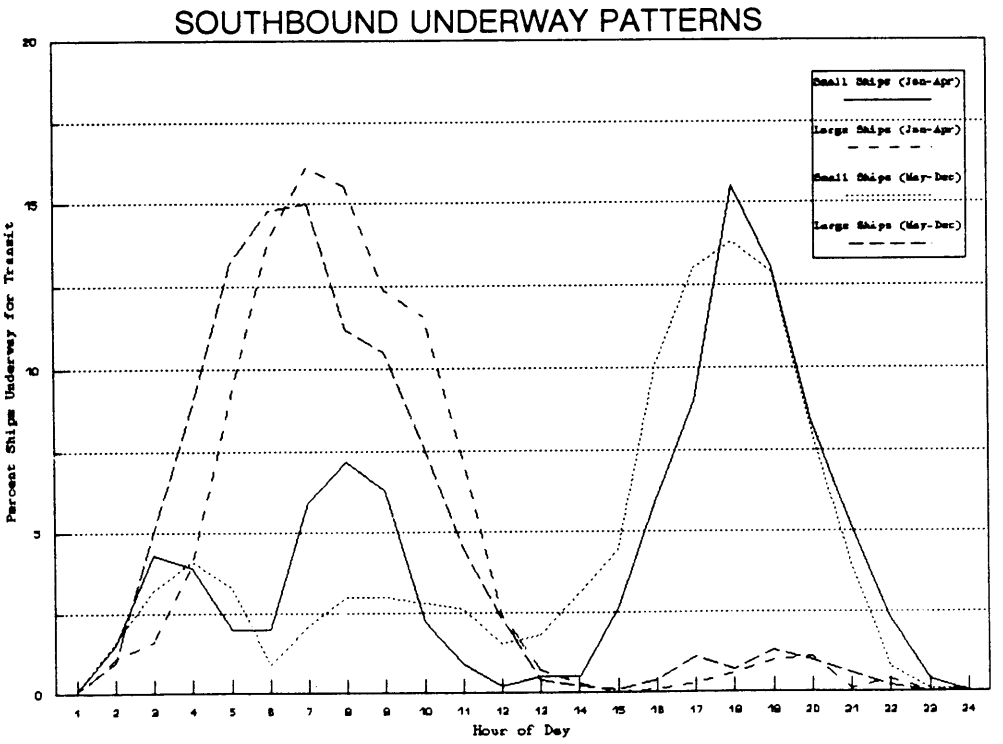


FIGURE 3-6

To incorporate both the random arrivals of ships and the scheduling practices in the simulated scenarios where channel widths in the Culebra Cut necessitate size-based ship scheduling, ship lists were generated in two stages for each such case. First, the specified number of ships were generated, assuming random (Poisson) arrivals. In the second stage these ships, each of which is treated as a separate arrival, were scheduled for transit through the Canal according to the logic described below.

- In general, all the ships in a given size category (large or small) are scheduled on a first-come-first-served basis. That is, no small ship can be scheduled ahead of other small ships that arrived earlier in a given direction of travel. The same logic applies to large ships also.

- Between hours 22:00 and 04:00 (*Night Period*), only small ships are scheduled and large ships are kept waiting.

- Between hours 04:00 and 10:00 (*Morning Period*) large ships are given preferential treatment. During this period, first large ships that arrived after hour 22:00 of the previous day are scheduled. These ships are followed by other large ships that arrived between hr 04:00 and the scheduled time of the last overnight large ship. After these two batches of large ships plus any other large ships waiting for transit are scheduled, the queue containing small ships is serviced.

- Between hours 10:00 and 14:00 (*Day Period*), small ships are given preferential treatment. Large ships are allowed only if there are no small ships waiting in the queue.

- Between hours 14:00 and 22:00 (*Evening Period*), large and small ships are serviced on first-come-first-served basis.

To generate lock downtime data (see discussion of simulation model and procedures in Chapters 5 and 6) to represent the occurrence of fog, published summary data from *The Panama Canal Pilot* about the historical occurrence of fog at Pedro Miguel were used. Figures 17-12 and 17-13 (page 409) in that publication give graphs of the percent of days with fog, and the beginning and ending times of fog at Pedro Miguel. Grids were superposed on the graphs, and the daily probability of fog (by month) and probabilities for starting and ending times (quantitized into 0.1-hr. intervals) were estimated.

Using a spreadsheet, days to have fog were chosen randomly, consistent with the observed probabilities, and start times were randomly assigned, again consistent with the observed distribution. Stop times were randomly chosen consistent with the conditional probabilities estimated from the graphs, given the assigned start times. Fog duration, of course, is stop time minus start time.

The required downtime file was then generated in proper format using a word processor to edit the spreadsheet print file.

A spreadsheet graph of cumulative distribution of fog start times manually estimated for historical Pedro Miguel data appears in Figure 3-7.

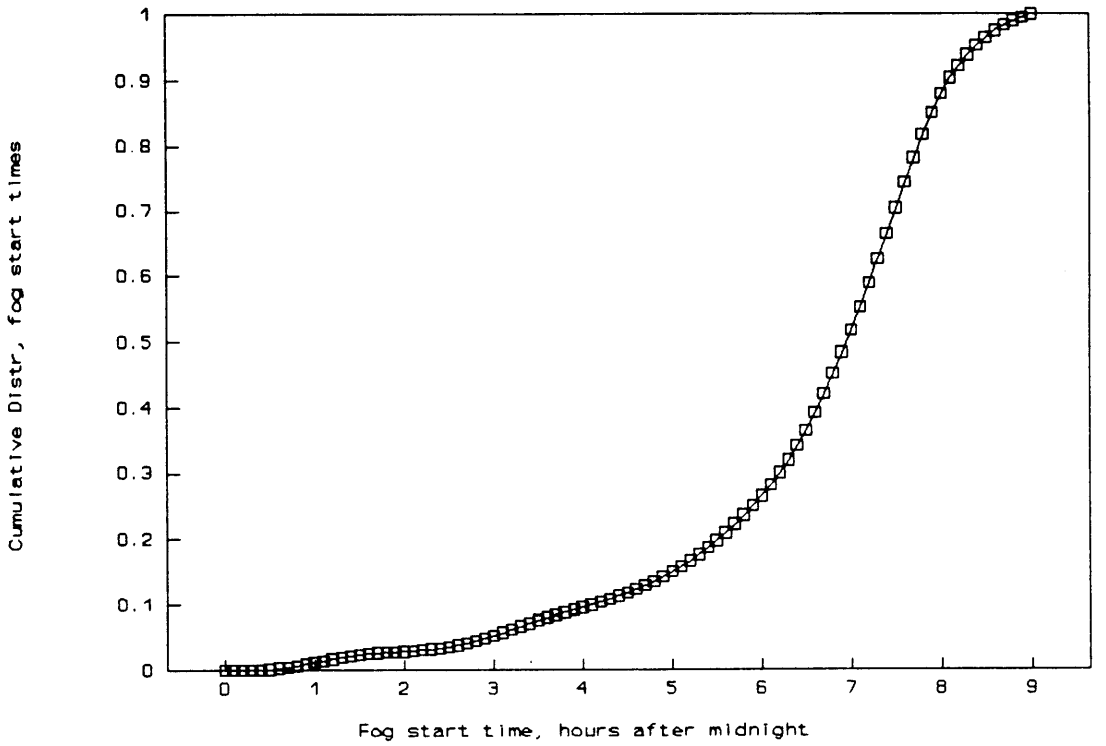


FIGURE 3-7

CHAPTER 4

TIDAL HYDRAULIC STUDIES AND MEASURES TO COUNTERACT TIDAL INFLUENCES

INTRODUCTION

Specifications for Model Analysis

Studies were made to analyze the tide levels and speeds in a sea-level canal and their variations due to changes in the tides in the two oceans (Figure 4-1). TAMS' Program LATIS was used to formulate a mathematical model of the canal. This model resolves the vertically integrated equations of motion in an open channel, the Saint Venant equations, in an explicit finite difference scheme. The model allows the introduction of modifications without substantial changes in its overall structure. Figure 4-2 is a schematic flow diagram of the Program, which uses links and nodes to represent the system. The volume of the system is represented by increments corresponding to each of the nodes, where the program computes water surface elevations at discrete intervals. The links are canal segments limited by adjacent nodes, where discharges are computed using the same time interval.

The computations start with the definition of parameters followed by that of the nodes and the links. Node volumes are introduced with tables of volumes versus water surface elevations. Link characteristics are introduced with tables of top widths, areas, conveyances, and water surface elevations. The computation phase is conducted for each time interval first, calculating the elevations for all nodes and then the discharges for all links, subject to various possible boundary conditions. Additional details are presented in Appendix B.

The initial runs of the model were made to ascertain its stability requirements; the time required for the model to reach steady state after starting from arbitrary initial conditions; and the computer operation time necessary to simulate the tides during an adequate period of time.

The various alternatives for which tidal currents were studied with the aid of this model are (Figure 4-3):

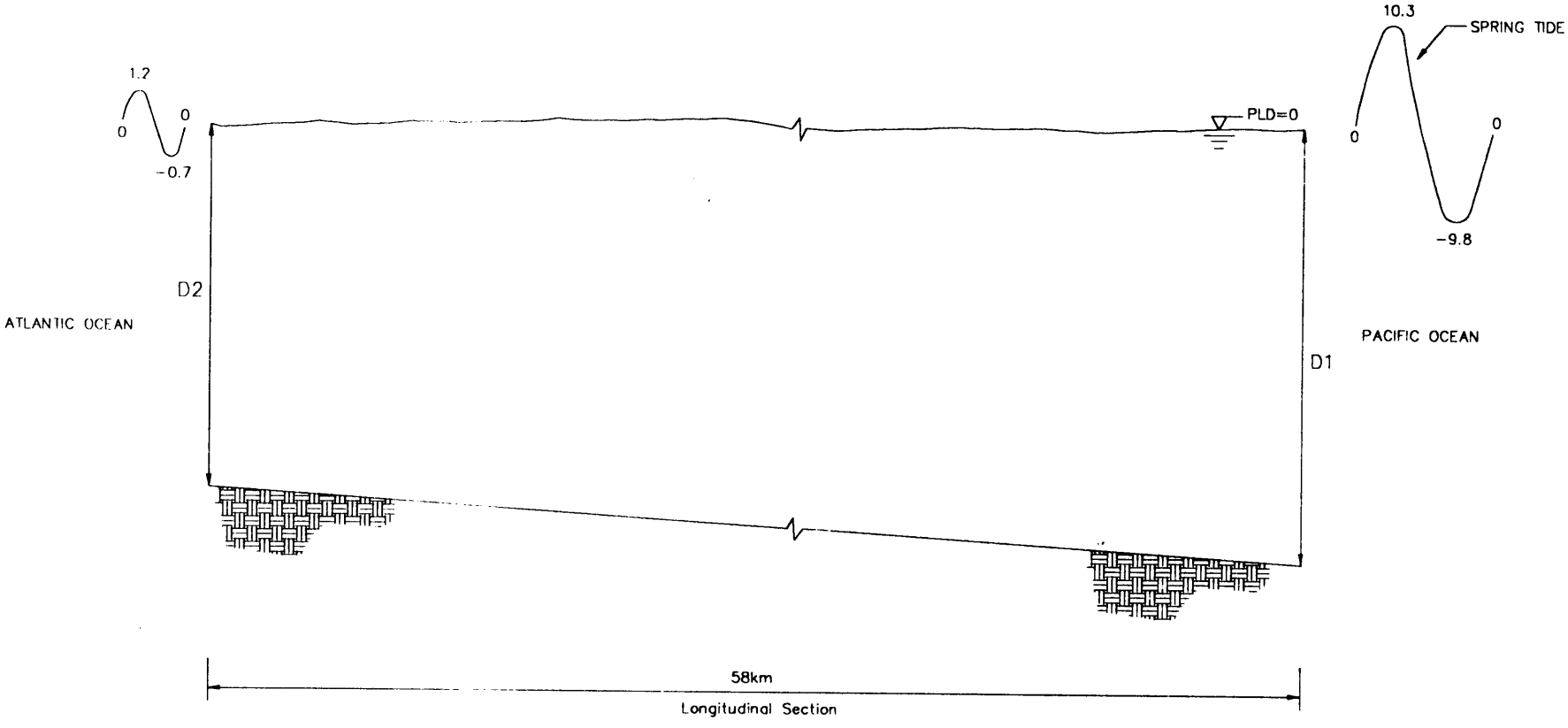
(1) 180m-wide canal, single lane traffic, 58 km long.

(2) 425m-wide canal, two lane traffic, 58 km long.

(3) Gates at both ends of the 58 km, 180m-wide canal.

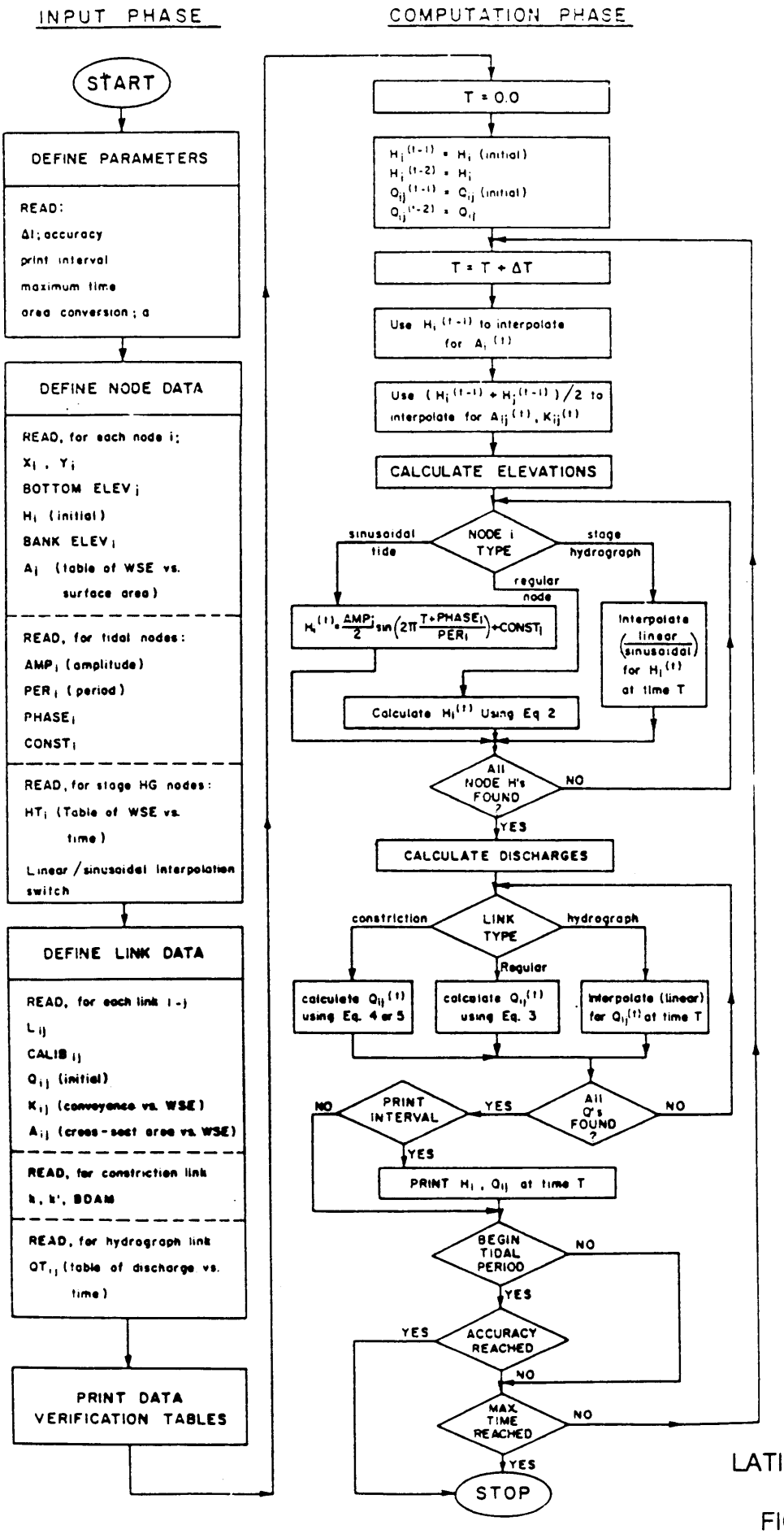
(4) Gates flanking 40 km single lane section with Pacific end at 16 km.

SEA-LEVEL PANAMA CANAL



D = LLSWL + 1.1 Draft of Design Ship
LLSWL = Lowest Lower Water Level
PLD = Precise Level Datum

FIGURE 4-1



LATIS MODEL

FIGURE 4-2

CANAL ALTERNATIVES

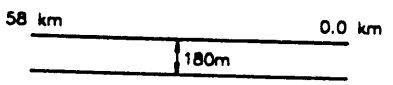
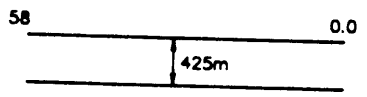
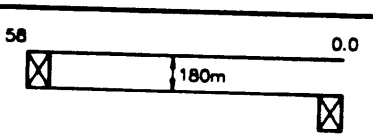
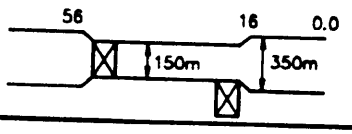
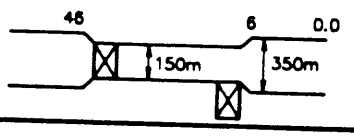
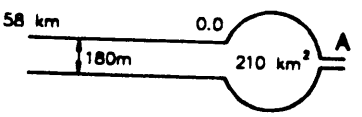
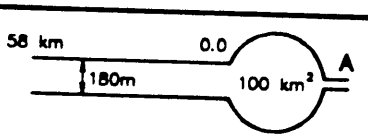
CASE TESTED	CONFIGURATION OF CANAL (Atlantic End – Pacific End)	ELEVATION OF BOTTOM AT PACIFIC END
① WITHOUT GATES		−28.7m
② WITHOUT GATES		−28.7m
③ GATES AT 58 & 0.0 Km		−28.7m
④ GATES AT 56 & 16 Km		−24.5m
⑤ GATES AT 46 & 6 Km		−24.5m
⑥ VERGARA ALTER. I		−28.7m
⑦ VERGARA ALTER. II		−28.7m

FIGURE 4-3

(5) Gates flanking 40 km, single lane section with Pacific end at 6 km.

(6) Vergara Alternative I, with a 210 km^2 basin at the Pacific end. This configuration required the addition of a quasi two-dimensional area at the Pacific end of the model.

(7) Vergara Alternative II, with a 100 km^2 basin at the Pacific end.

The distances along the canal were measured with respect to the Pacific Ocean end of the canal without the offshore embayment considered in the Vergara alternative. Station 0.0 km refers to the Pacific end and 58 km refers to the Atlantic end.

Previous Hydraulic Analyses

The hydraulics of the sea-level canal have been studied previously by the U.S. Army Corps of Engineers (Stratton et al. 1948, and Harleman, 1968 and 1969).

In earlier studies (Meyers and Schultz, 1948) calculations and physical models were used to compute maximum tidal velocities. An overall Manning's 'n' coefficient of 0.024 was adopted for the whole length of the canal. The maximum tidal speeds computed for a 6m (20 ft) tide in the Pacific were 4.5 knots for the Atlantic end and 3.7 knots for the Pacific end.

Harleman and collaborators (1968/9) made numerical tidal analyses for sections excavated with conventional and nuclear explosives. For the conventional canal they used a Manning's 'n' of 0.025. The maximum speed calculated for a straight 250 x 22m (800 x 70 ft) canal at its Atlantic end and for extreme tidal range was 4.7 knots.

BOUNDARY TIDES

The U.S. National Oceanic and Atmospheric Administration publishes tidal predictions for Balboa, at the Pacific end of the Canal and for Cristobal (Colon), at its Atlantic end. Tides predicted for the month of January 1992 were used as boundary conditions.

Figures 4-4 and 4-5 show the highs and lows for Balboa and Cristobal, respectively, in feet referred to Precise Level Datum (PLD). The Mean Tide Level (MTL) for Balboa has been established at 0.9 ft. above PLD. The MTL for Cristobal has been established at 0.14 ft. above PLD. The levels shown in Figures 4-4 and 4-5 have been adjusted to PLD as the predicted tides are referred to local datums for navigation purposes. Both figures have been drawn to the same scale to show the differences in predicted tides.

PREDICTED TIDES FOR BALBOA
JANUARY 1992

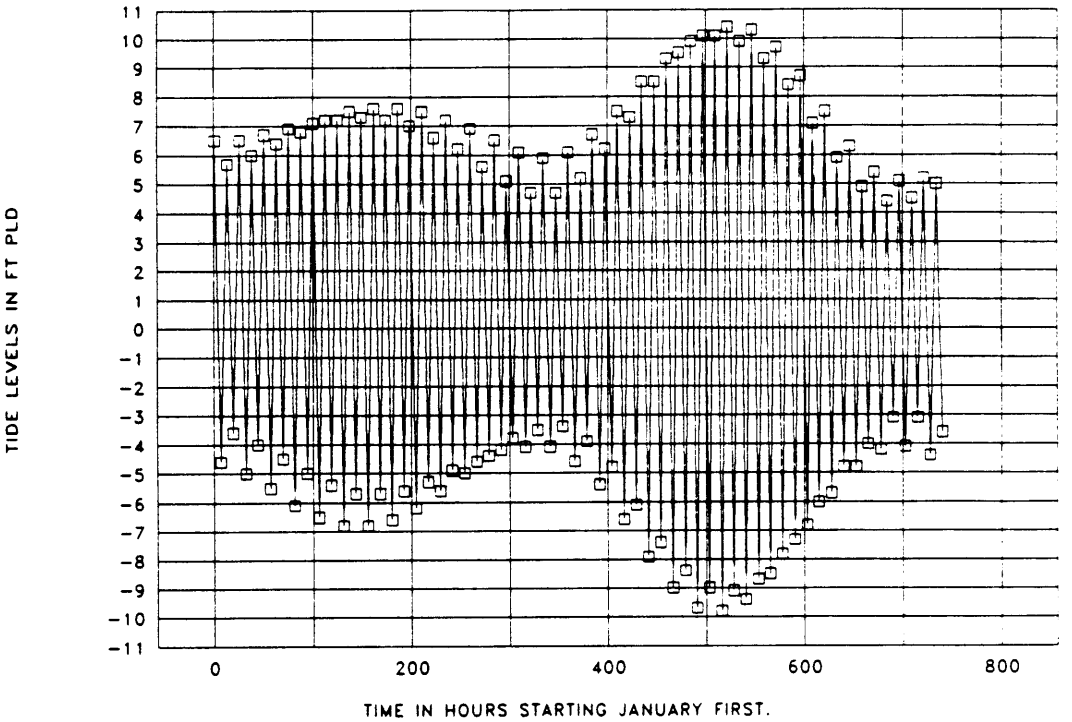


FIGURE 4-4

PREDICTED TIDES FOR CRISTOBAL
JANUARY 1992

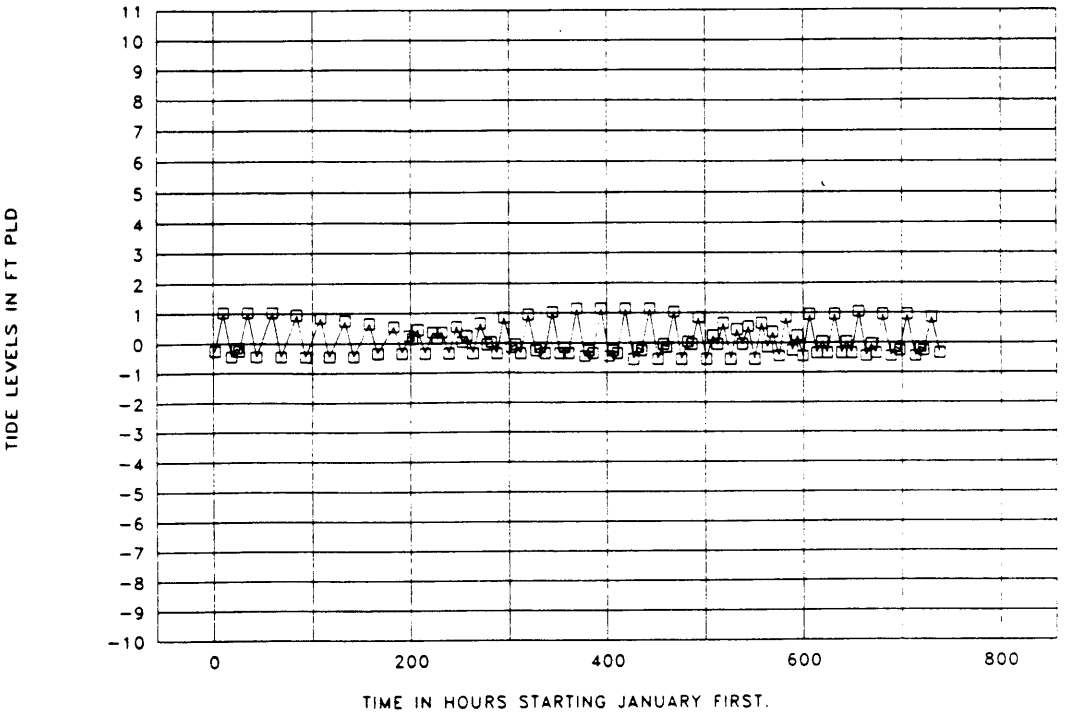


FIGURE 4-5

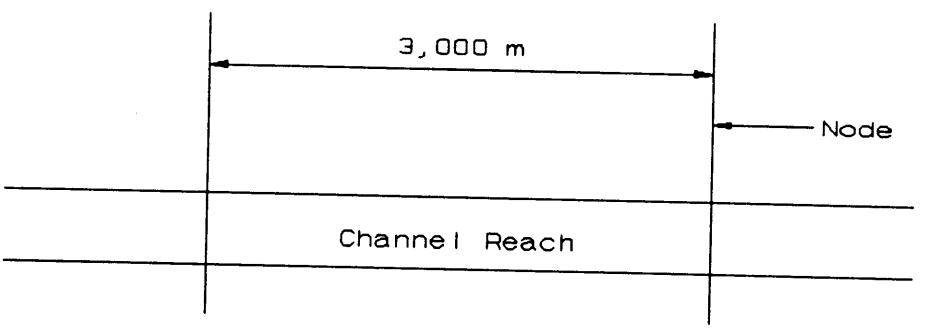
To represent a neap tide period the model was run for 120 hours starting with the Balboa low tide of January 13, at 15h 22m, or about 310 hours after the beginning of the month. The spring tide period was represented with an operation of 140 hours starting with the Balboa low tide of January 20, at 10h 01m, or about 470 hours after the beginning of the month. Figure 4-4 shows the Pacific neap and spring tides predicted respectively for 310 and 470 hours. The simultaneous tides for Balboa and Cristobal were input in the model referred to a common starting time, for either neap or spring tides, by subtracting respectively 310 or 470 hours from the predicted tide times.

The differences between neap and spring tides can be seen in Figure 4-4 (Balboa). Figure 4-5 shows that the tides in the Atlantic are mixed.

Only high and low water levels shown in Figures 4-4 and 4-5 were input in the LATIS Model, which then proceeded to obtain intermediate levels through sinusoidal interpolation between consecutive pairs of input values.

LINK AND NODE DEFINITION -- ROUTE 10

For the Route 10 alignment, the total length of 58 km (not including the embayments proposed by Vergara) was divided into 19 reaches (links), each about 3,000m long and defined by consecutive nodes in a linear arrangement.



The Vergara embayment on the Pacific side was represented by a quasi two-dimensional arrangement of nodes, as shown in Figure 4-13.

The channel cross-section was assumed to be trapezoidal with 1:2.5 side slopes. For the first model runs, the bottom elevation was assumed to change linearly from -29m (-94.2 ft) PLD at the Pacific end to -26m (-84.3 ft) PLD at the Atlantic end for the 180m-wide canal. The elevations consider the draft requirements at low tide for the different alternatives and reflect the substantial tidal range differences at both ends of the channel.

The hydraulic properties of the channel were calculated with TAMS Program PRELATIS, which processes geometric data for the channel cross-section and

produces tables of node volumes, cross-sectional areas, top widths and hydraulic conveyances in terms of water surface elevations. A Manning coefficient of 0.025 was used to compute the conveyances, consistent with the roughness value assumed in the previous studies.

The tables of properties were stored in files in the formats required by the main program LATIS, which interpolates their values for the finite difference resolution of the Saint Venant equations.

MODEL RUN CONDITIONS

After preliminary trial runs, a time interval of 50 seconds was selected for further analyses of the canal without the Vergara embayments as it resulted in a very stable model. In the latter case the selected time interval was 25 seconds.

A uniform water elevation of 0.04m (0.14 ft) PLD, equal to the mid-tide level at Cristobal, and zero discharge were assumed as initial conditions for the channel. For all practical purposes, model steady state was reached in about three or less tidal cycles, after instabilities resulting from that arbitrary initial model state were damped out. Thus the simulation times for neap and spring tides resulted in good samples of tidal cycles for analysis.

MODEL RESULTS -- ROUTE 10 -- TIDE LEVELS

Neap tide and spring tide simulations with tide levels were done for a 180m (600-ft) wide channel (Case 1).

Neap Tide Simulation

Figure 4-6 shows a graph of tide levels versus time obtained from the LATIS Model output after a 120 hr. real time neap tide simulation, starting on January 13, 1992.

Figure 4-6 shows the boundary tides on the Pacific and Atlantic ends of the channel and the levels for Node 13 (Mile 22.4--36 km). Tides obtained for all the nodes of the model are stored on disk files.

Although the model computations progress at 50-second intervals, printout values are requested at intervals of one hour. Such values are represented in Figure 4-6.

Spring Tide Simulation

Figure 4-7 is a graph of water levels versus time obtained with the model for spring tide conditions, starting, as noted previously on January 20, 1992. As before, Figure 4-7 shows the tides computed at Node 13, and for both ends of the canal. Levels computed for the other nodes from 2 to 19 are stored in disk files.

PANAMA CANAL - ROUTE 10 - TIDE LEVELS
BOTTOM WIDTH: 180 M (600 FT)

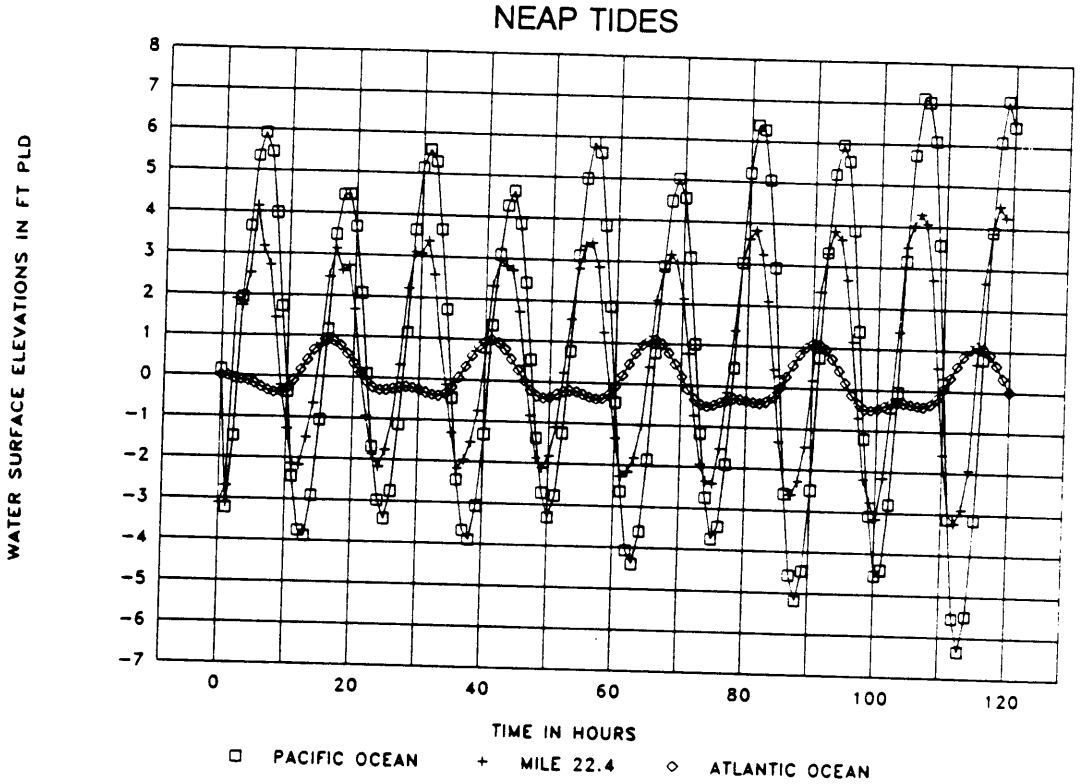


FIGURE 4-6

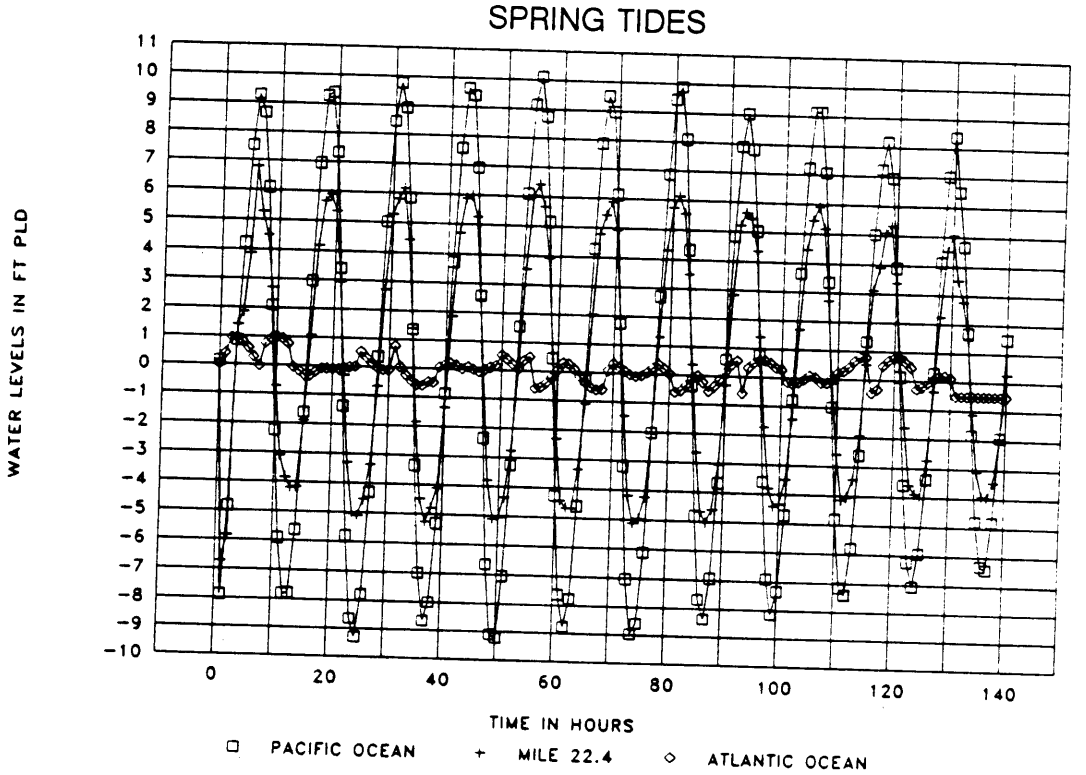


FIGURE 4-7

MODEL RESULTS FOR CURRENT VELOCITIES

General

The critical flow conditions in the canal occur during spring tides. The analyses below, therefore, were made only for spring tides.

Case 1

Figure 4-8 is a graph of tidal water speeds in knots, also for spring tide conditions. Northbound velocities (toward the Atlantic) are presented as negative in the graph. The minimum/maximum northbound velocity during the spring tide was computed at about 5.2 knots.

Southbound velocities (toward the Pacific) are considered positive. It may be observed that maximum velocities toward the Atlantic tend to be about 1.2 knots faster than those toward the Pacific. As stated above, the cross-section at the Atlantic end of the canal is shallower than at the Pacific end. In addition, the Pacific range is considerably higher than the Atlantic range. Furthermore, the Pacific mid-tide level is higher than the Atlantic mid-tide level.

The model demonstrated that maximum discharge lags are, in general, short.

Case 2

For this alternative the width of the canal was set at 425m (1,400 ft) for the entire length. Figure 4-9 shows sequences of speeds computed in this run for both ends of the canal and for km 36 (Mile 22.4) as well. The figure shows that the computed maximum velocity at the Atlantic end is 5.5 knots. Velocities are slightly higher than for Case 1 because of the reduced effect of side wall friction.

Cases 3, 4, and 5

These alternatives would include gates at both ends of the canal or at intermediate points. The gates would be closed to avoid the high speeds that would occur in a free flowing canal.

Case 3 would provide a 180m (600 ft)-wide canal for its entire length, with gates at both ends. The LATIS Model was run assuming that the Atlantic gate would be closed, to find the maximum tidal speeds with a continuous closure. Figure 4-10 shows current speeds obtained in this run. The figure shows that the maximum speed for the Pacific end would be about 2.2 knots. A comparison with Case 1 shows the sharp reduction in currents that result from the introduction of tide gates.

PANAMA CANAL - ROUTE 10 - WATER SPEEDS

58 KM LONG, 180 M (600 FT) WIDE CANAL, SPRING

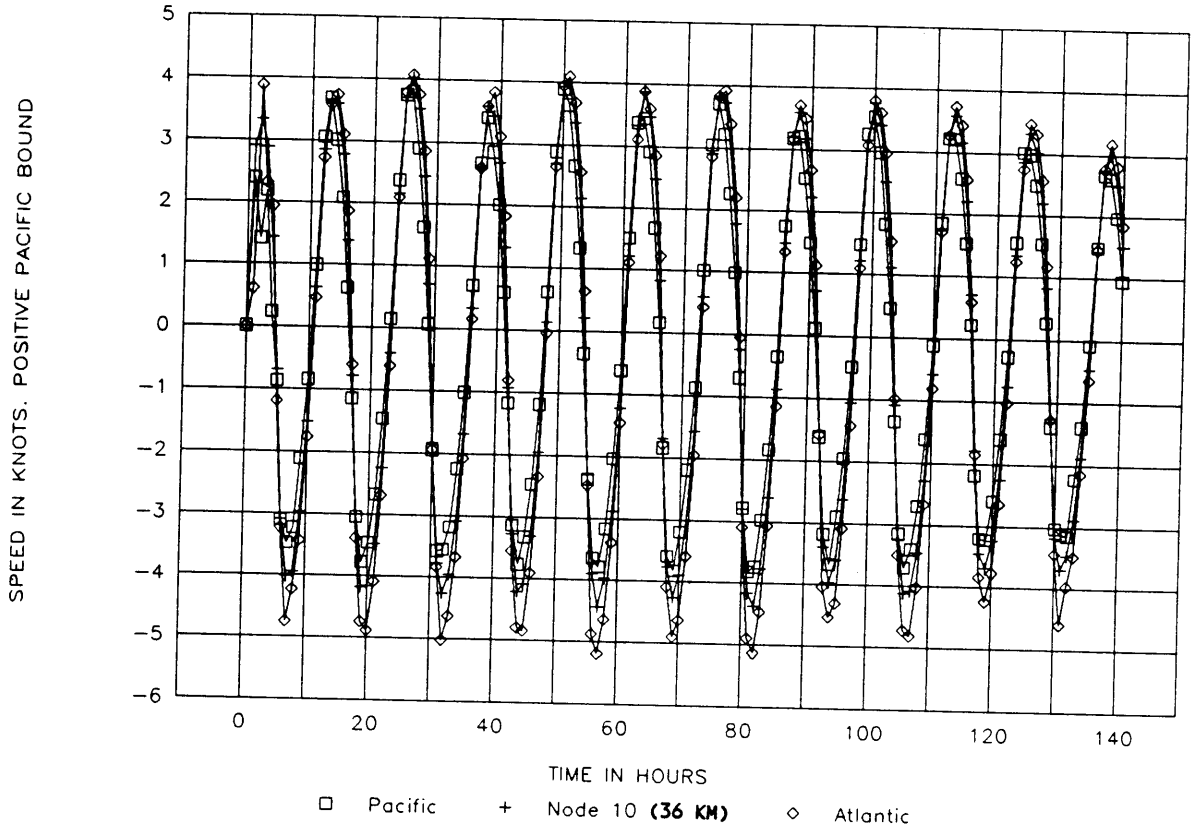


FIGURE 4-8
Case 1

PANAMA CANAL - ROUTE 10 - WATER SPEEDS

58 KM LONG, 425 M (1,400 FT) WIDE CANAL

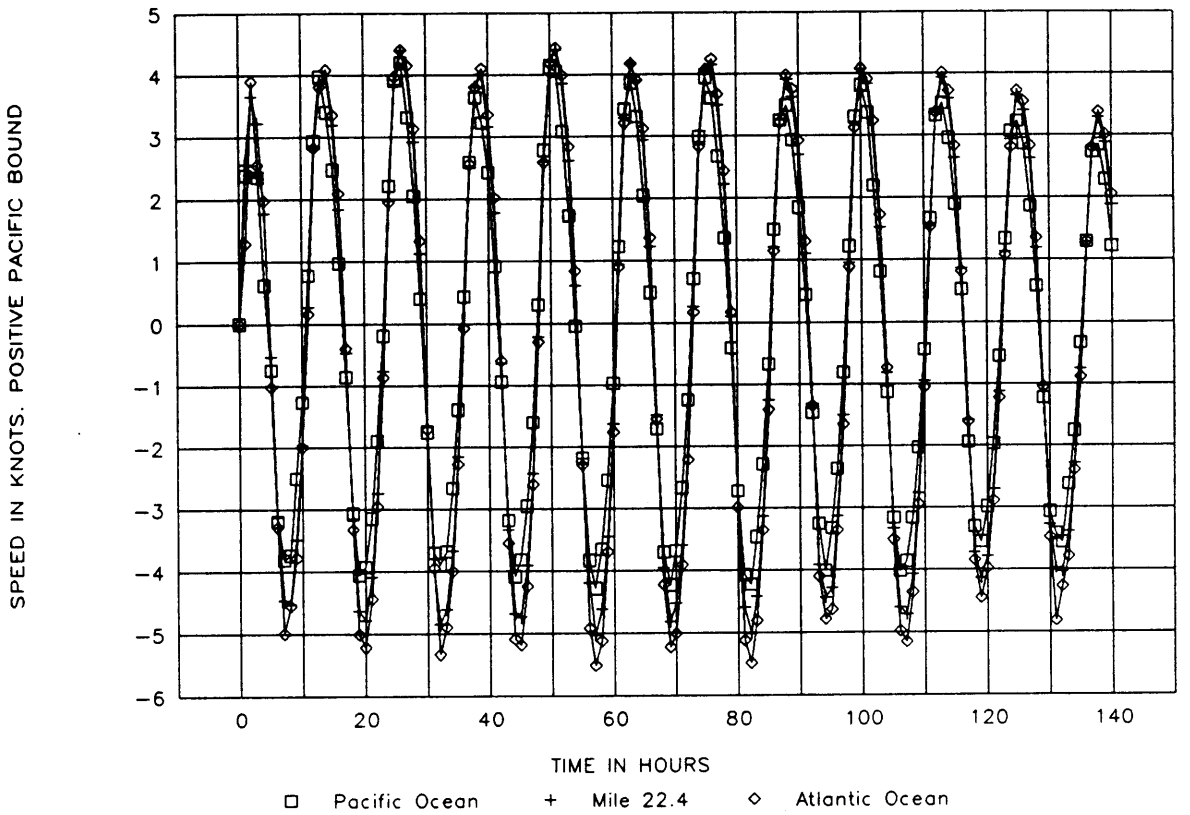


FIGURE 4-9
Case 2

PANAMA CANAL - ROUTE 10 - WATER SPEEDS

58 KM LONG, 180 M (600 FT) WIDE, GATE ATLANTIC

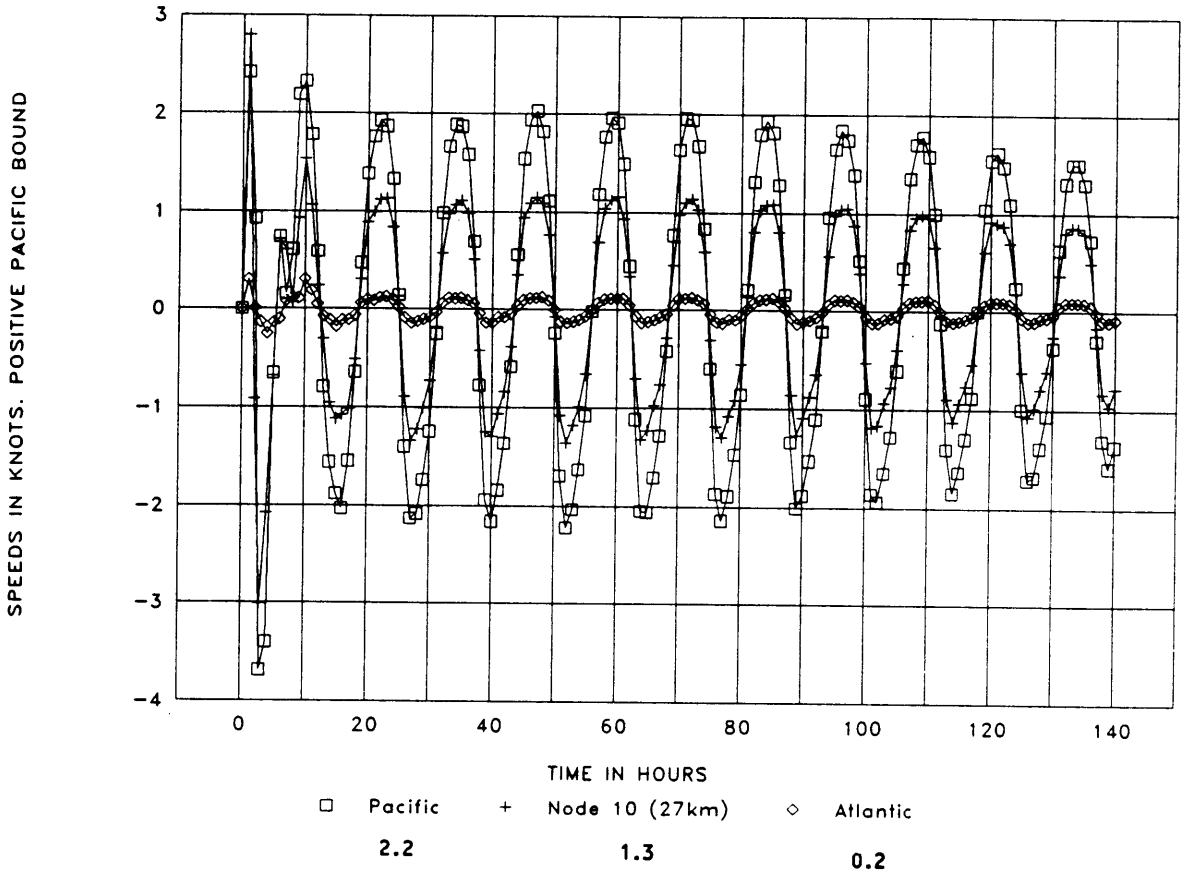


FIGURE 4-10
Case 3

Case 4 would provide a central canal width of 150m (500 ft) with end reaches of 350m (1,125 ft), as shown in Figure 4-3. A continuous closure of a tidal gate located at km 56 from the Pacific end would result in a maximum speed of 1.5 knots at the Pacific. This velocity is lower than produced under Case 3 because not only is the length from the Pacific to the gate shorter but the cross-section at the Pacific is larger. Figure 4-11 shows sequences of speeds obtained in this run.

Case 5 would provide the same widths as Case 4, 350m and 150m (1,125 ft and 500 ft) but the central portion would be located between km 6 and km 46 from the Pacific end. Figure 4-12 show sequences of speeds computed in this run. The figure shows that this alternative would result in a further reduction in computed maximum speed to 1.0 knot.

Vergara Alternatives (Cases 6 and 7)

These alternatives would include the construction of an embayment off-shore of the Pacific end of the canal. Two different sizes of embayments: 210 sq km (21,000 ha) and 100 sq km (10,000 ha), were analyzed.

The first of these, with an embayment approximately 16 km-long by 13 km-wide, involved a quasi two-dimensional portion of the model with eight, 3,000m-long by 1,800m-wide, rectangular elements, as shown in Figure 4-13. This network was assumed connected to the Pacific Ocean through a 2,950m-long link with hydraulic characteristics equal to the first link (Pacific side) of Case 1.

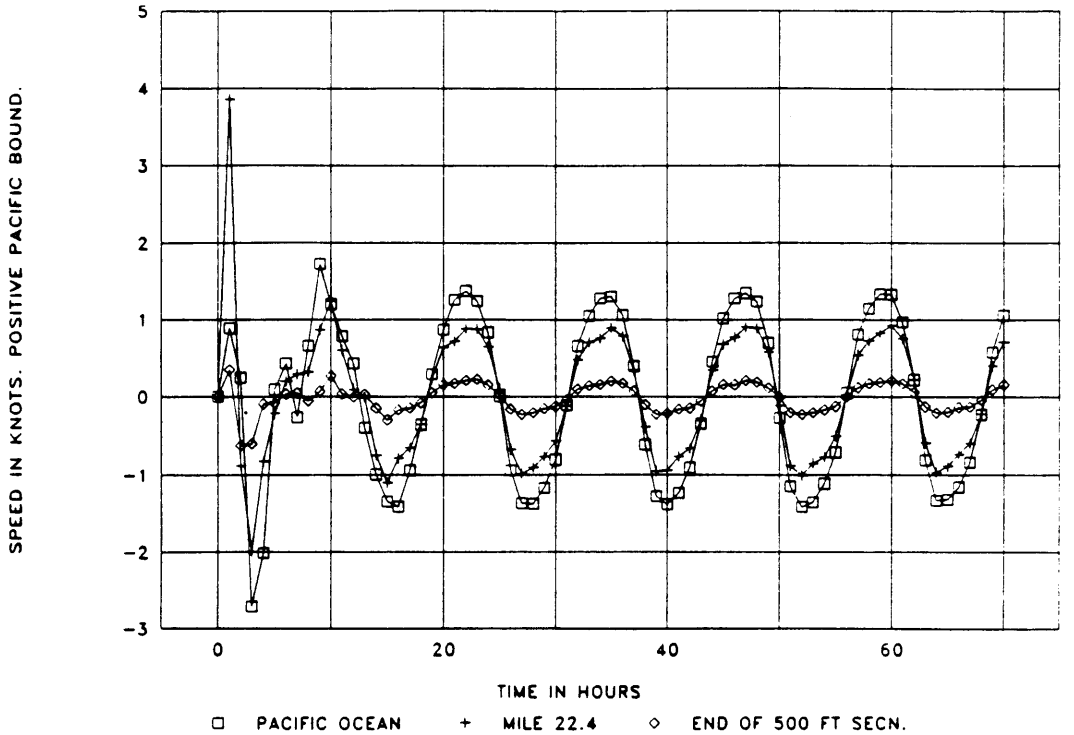
Figure 4-14 shows a comparison of sequences of tidal speeds, at the breakwater entrance connecting the embayment and the Pacific Ocean, and at km 0, 36 and 58 on the 180m-wide canal, equivalent to the canal analyzed for Case 1. The computed maximum speeds in the canal were reduced from 5.2 knots for Case 1 to 4.3 knots, not a significant reduction. Moreover, the maximum computed speed at the breakwater entrance was 17 knots. Figure 4-14 shows that during 75 percent of the time the entrance speed would be higher that 6 knots. In addition to the navigation implications of such speeds, the currents would result in serious scour problems unless protective measures were effected.

Figure 4-15 shows the speed sequences for the case with 100 sq km embayment, and other conditions equal to those of the previous case. The maximum computed speed in the gap at the entrance to the embayment was close to 9 knots with speeds of 4 knots or more prevailing for more than 80 percent of the time. The maximum speed computed at the Atlantic end of the canal was 4.7 knots.

Although the maximum speeds in the gap would be less than for the case with a 210 sq km embayment, they would still be erosive without suitable bottom protection. On the other hand, the speeds in the canal would be faster and not much different than those obtained for the comparable case without embayment (180m-wide canal). Figure 4-16 summarizes the results of the tidal hydraulics analysis of the various alternatives.

PANAMA CANAL - ROUTE 10 - WATER SPEEDS

WIDTH: 345/150/345 M (1,125/500/1,125 FT) GATE 150 M (500 FT) FROM END



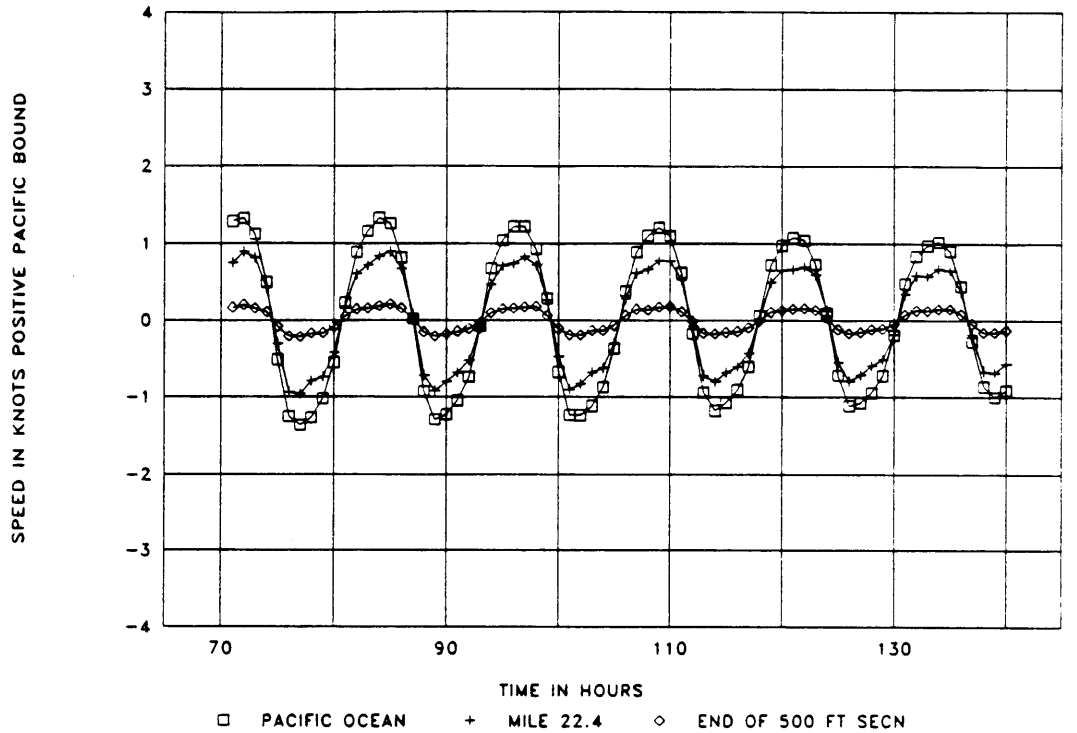
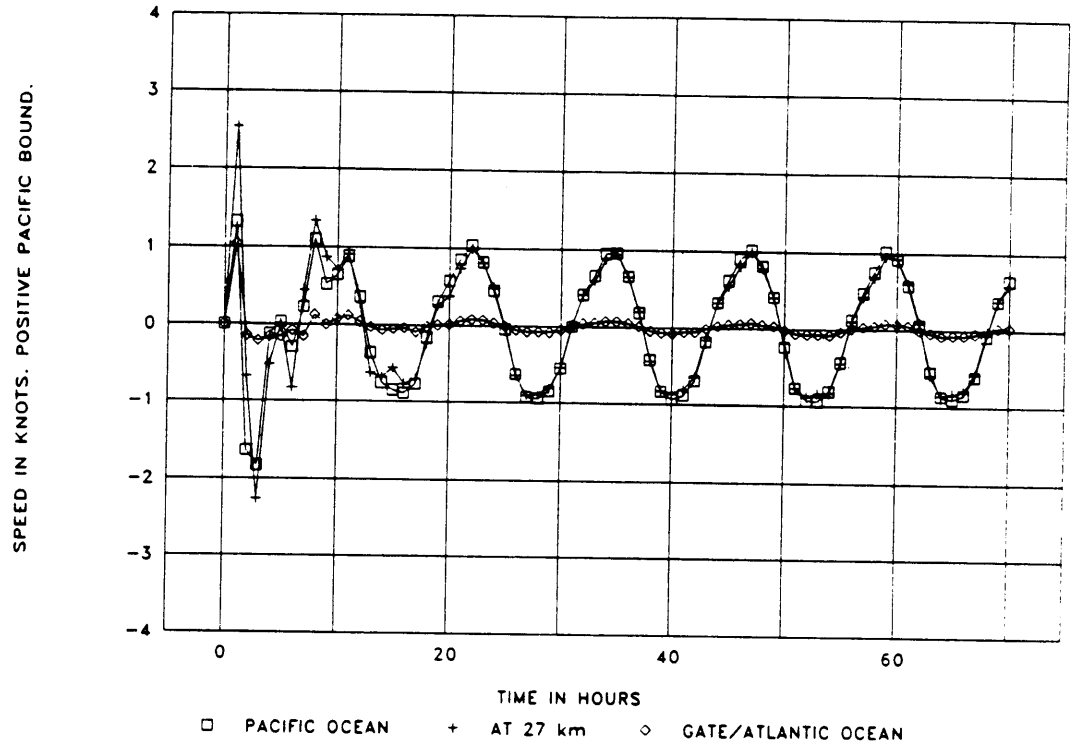


FIGURE 4-11
Case 4

PANAMA CANAL - ROUTE 10 - WATER SPEEDS

150 M (500 FT) BEGINS AT 6 KM FROM PACIFIC



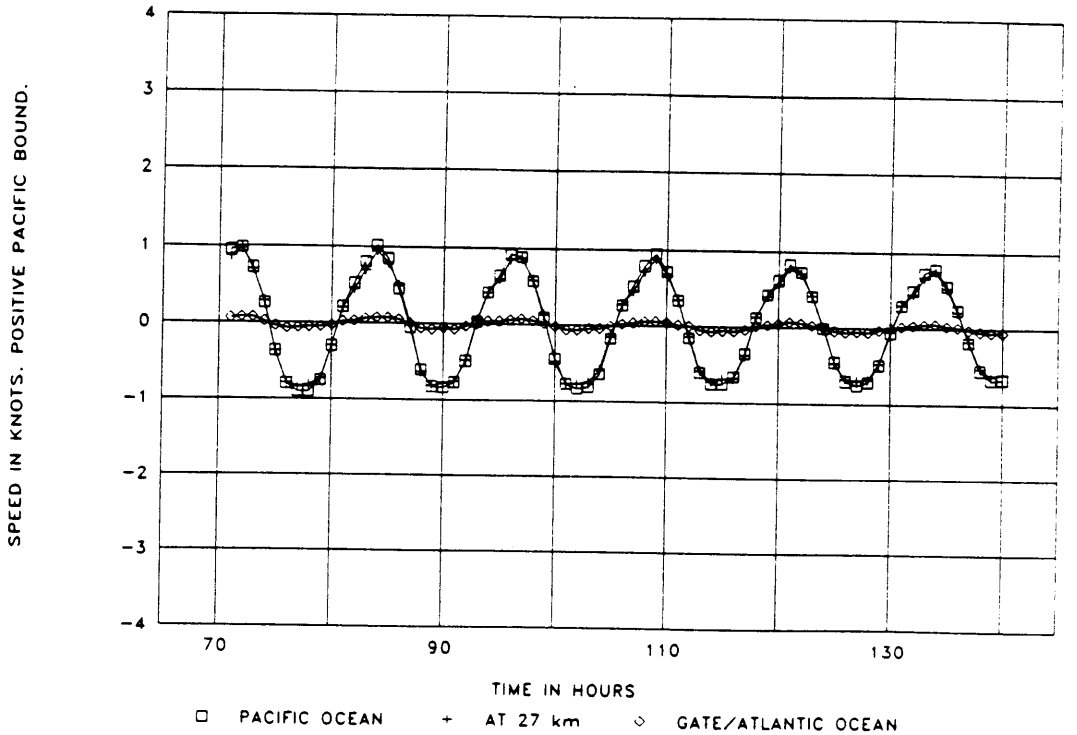
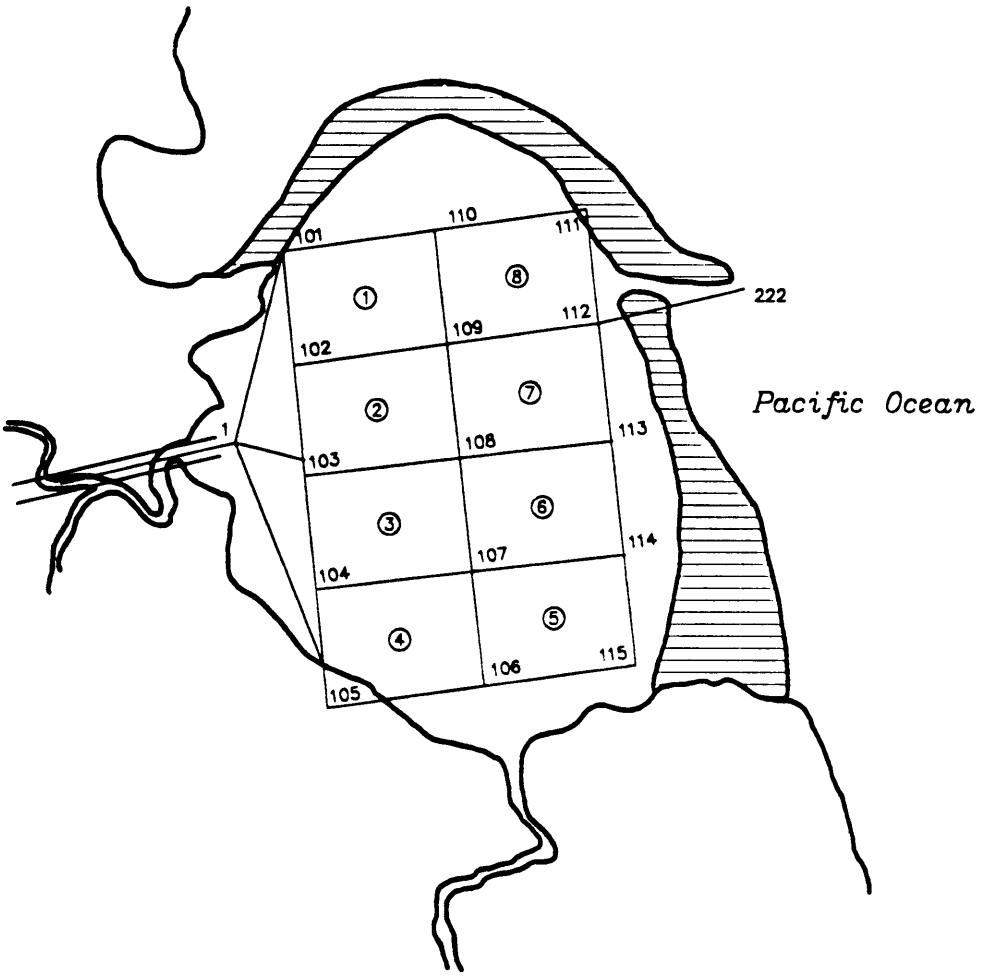


FIGURE 4-12
Case 5

VERGARA ALTERNATIVE

REPRESENTATION OF THE EMBAYMENT : ELEMENTS AND NODES



① : Element Number

102 : Node Number

Alt. 1 : Embayment - 210 sq.km.
Entrance Width - 600m

Alt. 2 : Embayment - 100 sq.km
Entrance Width - 600m

FIGURE 4-13

THE VERGARA ALTERNATIVE

BAY AREA = 210 SQ KM

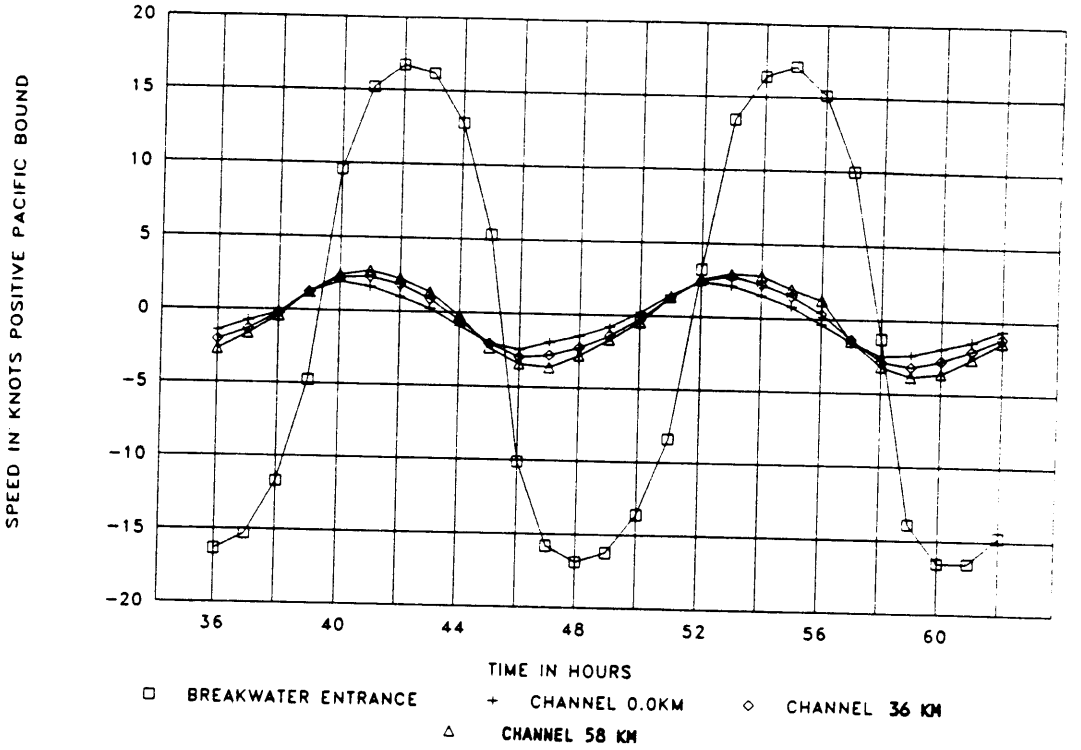


FIGURE 4-14

BAY AREA = 100 SQ KM

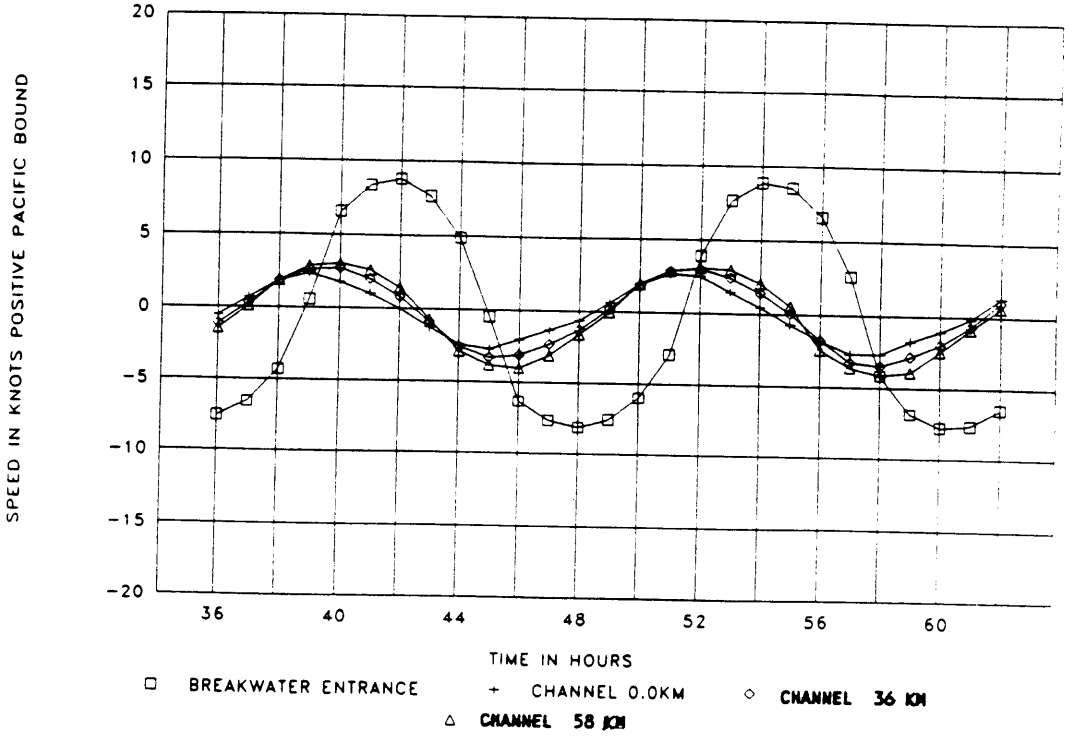
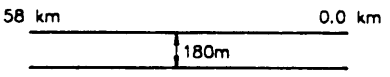
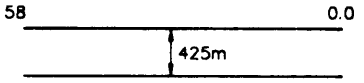
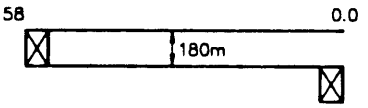
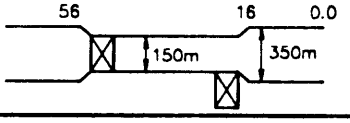
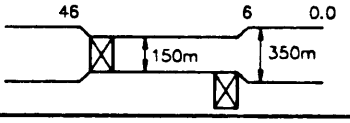
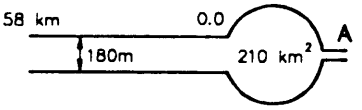
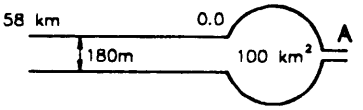


FIGURE 4-15

RESULTS OF LATIS ANALYSIS

CASE TESTED	CONFIGURATION OF CANAL (Atlantic End – Pacific End)	ELEVATION OF BOTTOM AT PACIFIC END	MAX. WATER SPEED (Knots)			
			58 km	36 km	0.0 km	A
① WITHOUT GATES		−28.7m	5.2	4.2	4.0	–
② WITHOUT GATES		−28.7m	5.5	4.7	4.2	–
③ GATES AT 58 & 0.0 Km		−28.7m	0.2	1.3	2.2	–
④ GATES AT 56 & 16 Km		−24.5m	* 0.4	1.0	1.5	–
⑤ GATES AT 46 & 6 Km		−24.5m	0.0	** 1.0	1.0	–
⑥ VERGARA ALTER. I		−28.7m	4.3	3.3	3.1	17
⑦ VERGARA ALTER. II		−28.7m	4.7	3.9	3.4	9

All of the results refer to the spring tide situation.
Manning's Number = 0.025, which is a measure of channel roughness.
* Max. water speed refers to a location 56 km from the Pacific entrance.
** Max. water speed refers to a location 27.0 km from the Pacific entrance.

FIGURE 4-16

Sensitivity Analyses

The LATIS Model was run to test its response to changes in the range of Manning's coefficients assumed to represent the roughness of the canal.

This computation was made changing the value of this parameter from 0.025 to 0.035 for the Route 10 Alternative with a 180m-wide canal and no gates. The spring tide sequences previously used were assumed for the boundary conditions at both ends of the canal. The maximum computed speed was reduced by about 1.2 knots.

Maximum Water Speed (Knots)
(See Figure 4-3)

Case 1	@ 58 km	@ 0.0 km
Manning Coefficient .025	5.2	4.0
Manning Coefficient .035	4.0	2.8

The roughness coefficient of 0.035 used in the sensitivity tests is higher than the upper boundary of the admissible range for a man-made canal of the magnitude of the Panama Canal. The computed reductions in maximum speeds, however, did not change the result with respect to navigation feasibility.

INFLUENCE OF TRIBUTARY DISCHARGES ON CANAL SPEEDS

The overall influence of flood discharges in the streams intercepted by Route 10 on the maximum speeds in the canal will be very small.

All important streams from the east are intercepted by the present canal, including the Chagres River. Streams from the west are less important. For example, the Rio Trinidad, gaged since 1947, had a maximum peak discharge of 10,154 cfs at Chorro on September 11, 1955, the largest of record. The Ciri Grande had a maximum gaged discharge of 9,032 cfs at Los Cañones on December 31, 1949.

On the other hand, the tidal discharges computed for all alternatives of the sea-level canal are at least one order-of-magnitude larger than those instantaneous peak discharges.

The alternative with closed gate at km 46.0 and open gate at km 6.0, showed a maximum discharge from the Pacific toward the Atlantic of more than 144,000 cfs, with maximum speed of 1.0 knots.

Since the duration of the peak hydrologic discharges is very short, it is expected that they will be considerably attenuated by the large capacity of the canal, thus

further increasing the large difference between the tidal velocities and the increments due to flood discharges.

It is concluded that critical navigation conditions will not be significantly influenced by tributary discharges.

MEASURES TO COUNTERACT TIDAL INFLUENCES

The hydraulic analyses herein demonstrate that in an open channel between two oceans, peak currents resulting from spring tides at the Pacific end of the canal would exceed 5.0 knots. Most ships, but particularly ships larger than 100,000 DWT cannot navigate safely in a narrow channel with such swift currents. The navigation consultant's recommendations were that maximum allowable head currents should not exceed 2 knots/hr. and maximum allowable following currents should not exceed one 1 knot/hr (Appendix C).

Merely limiting the hours of navigation would severely restrict the capacity of the canal and is not practicable. Furthermore, a major safety problem would remain. If a large vessel were to break down, it would have to be moored to resist the peak currents without breaking loose--as would all other vessels caught behind it. If the vessel were aground or caught crosswise in the channel this would present a dangerous condition.

Therefore, various means of controlling currents have been considered.

In the preceding hydraulic analyses, the effects of tidal barriers at different locations in the sea-level canal have been investigated. In addition, the Vergara alternative, which would utilize a large embayment at the Pacific end of the canal to mitigate tidal effects, has been investigated. The analysis of the Vergara alternative indicates that currents in the canal would be reduced, but not sufficiently for safe navigation. Moreover, a very fast current would be created at the entrance to the embayment area. This entrance would not be navigable for much of the tidal cycle and it would be difficult to protect against severe scour at the ends of the breakwaters enclosing the embayment.

If only a single tide gate were used, because the gate could be operated only at slack tide, once open, it would have to remain open at least until the following slack tide, thereby exposing the canal to the full effect of the difference in tides between the oceans and nothing would be gained. Therefore, a system of positive closure involving two tide gates, or a set of locks, is needed. One or the other of the tide gates will always be closed, except during a brief period at half-tide on the Pacific side, when the water level is virtually the same throughout the length of the Canal. The tide on the Pacific side is diurnal and a full-tide cycle is 12½ hours; half-tide occurs every 6¼ hours and operating cycles would be keyed to these rhythms.

When the gate at the Atlantic end is closed, tidal fluctuations in the Pacific will affect only the portion south of the gate and, since this portion will be a closed embayment with limited area and length, tidal currents will be sharply reduced. Ships in convoy located within this portion of the canal will be able to exit to the Pacific and ships will also be able to enter from the Pacific. If the section has only one lane, the second convoy will need to wait for the first convoy to clear before it enters. This second convoy will proceed north and should travel at a speed that will bring the lead vessel to within the safe clearance distance from the gate at the Atlantic end as that gate is opened. At the same time the last vessel in the convoy must just clear the gate at the Pacific end, as it begins to close. With the gate at the Atlantic end open the convoy will proceed through the Atlantic approach and then out of the canal, so that the next Pacific-bound convoy can enter the canal (Figure 4-17).

With this arrangement of tide gates, it can be seen that the distance between gates, the length of the one-way section, vessel speed, the length of the operating cycle, the number of ships in a convoy and, therefore, the number of ships using the canal each day all become interdependent variables.

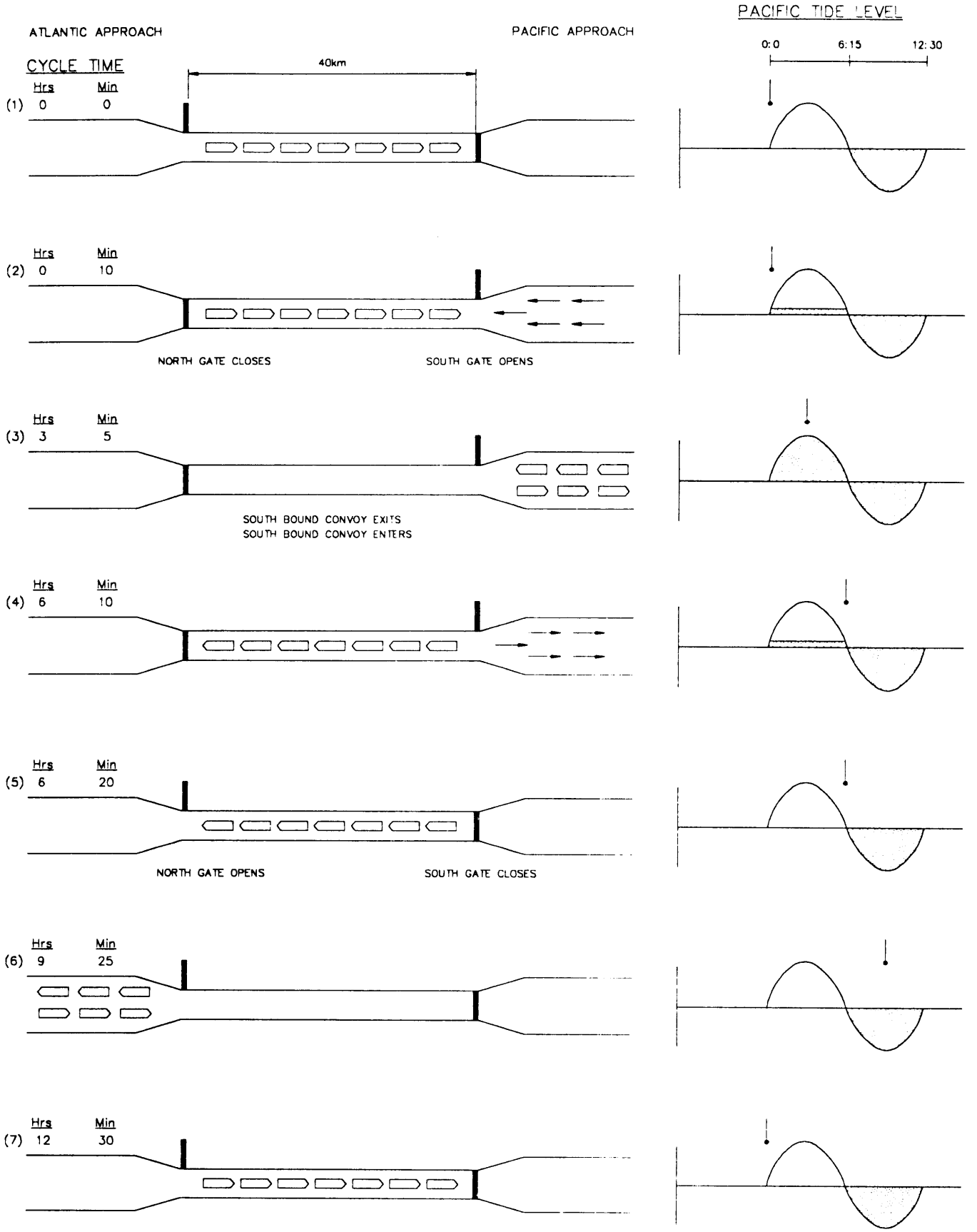
In order to select the most appropriate alternatives for detailed analysis using the WAM, a preliminary analysis of various sea-level canal configurations was made initially to test the comparative effects on capacity of different lengths of one-way sections, spacings of tide gates, different operating cycles of tide gates and different convoy lengths. Subsequently, the WAM was applied to the selected alternatives, and, using the WEFA forecasts of alternative ship mixes, the capacities of the most appropriate cases were computed.

Based on a maximum ship speed of 13 km/hour, it was determined for a full-tide cycle, that a canal with a single lane across the entire isthmus would have a capacity equivalent to shorter single-lane canals and, of course, would be cheaper to construct.

With half-tide cycle operations and the same maximum ship speed, the optimum length of single-lane canal section flanked by tide gates would be about 40 km.

For a canal with a tidal lock at the Pacific end instead of tide gates, assuming a 20-minute separation of ships and locking time of one hour, three parallel locks would roughly balance the capacity of a single-lane channel. A single-lane canal would require a cyclic, convoy-time operation to achieve maximum capacity. Although the timing of gate operations would be independent of the tide cycle, a 12½-hour cycle was selected nevertheless as the basis for the WAM analysis.

SEA-LEVEL CANAL TIDE GATE OPERATION



NOTE:
Shaded Area Indicates Water Level North of Pacific Tide Gate.

FIGURE 4-17

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CHAPTER 5

THE WATERWAY ANALYSIS MODEL

INTRODUCTION

The Waterway Analysis Model (WAM) has been in use by the U.S. Army Corps of Engineers for more than ten years. The purpose of WAM is to represent on a computer the operation of a waterway system in transporting waterborne cargo. WAM is a relatively large and detailed simulation model, providing explicit representation of individual waterway facilities, cargo consignments, and vessels.

WAM was originally developed to simulate shallow draft barge traffic on the U.S. inland waterways. The model has been used extensively to simulate parallel locks, and thus is directly applicable to the multi-lane Panama Canal operations.

The documentation for the inland waterway version of the model, hereafter called the IW-WAM, refers frequently to system specific attributes such as towboats, barges, river junctions, multiple cut lockage operations, and so on. The next section provides an overview level description of WAM, and was extracted from the IW-WAM documentation. Hence, it continues to use some terminology that is not appropriate for the Panama Canal. The subsequent section discusses how WAM was used to simulate Panama Canal operations.

Documentation of the Panama Canal versions of WAM was prepared as part of the OCCE Study, and will be delivered under separate cover.

MODEL DESCRIPTION

Overview

An overview of the structure of the Waterway Analysis Model is presented in Figure 5-1. The four major components are:

a. System Description Input Data

This is a set of input records which describes the waterway network (ports, locks, interconnecting channels), the vessel fleet, and the commodity classes to be transported.

b. External Event Input Data

These input records are read into the model during the simulation process and trigger occurrence of events. There are three types of external event input: 1) shipment data, 2) run control data, and 3) lock downtime events.

STRUCTURE OF THE WATERWAY ANALYSIS MODEL

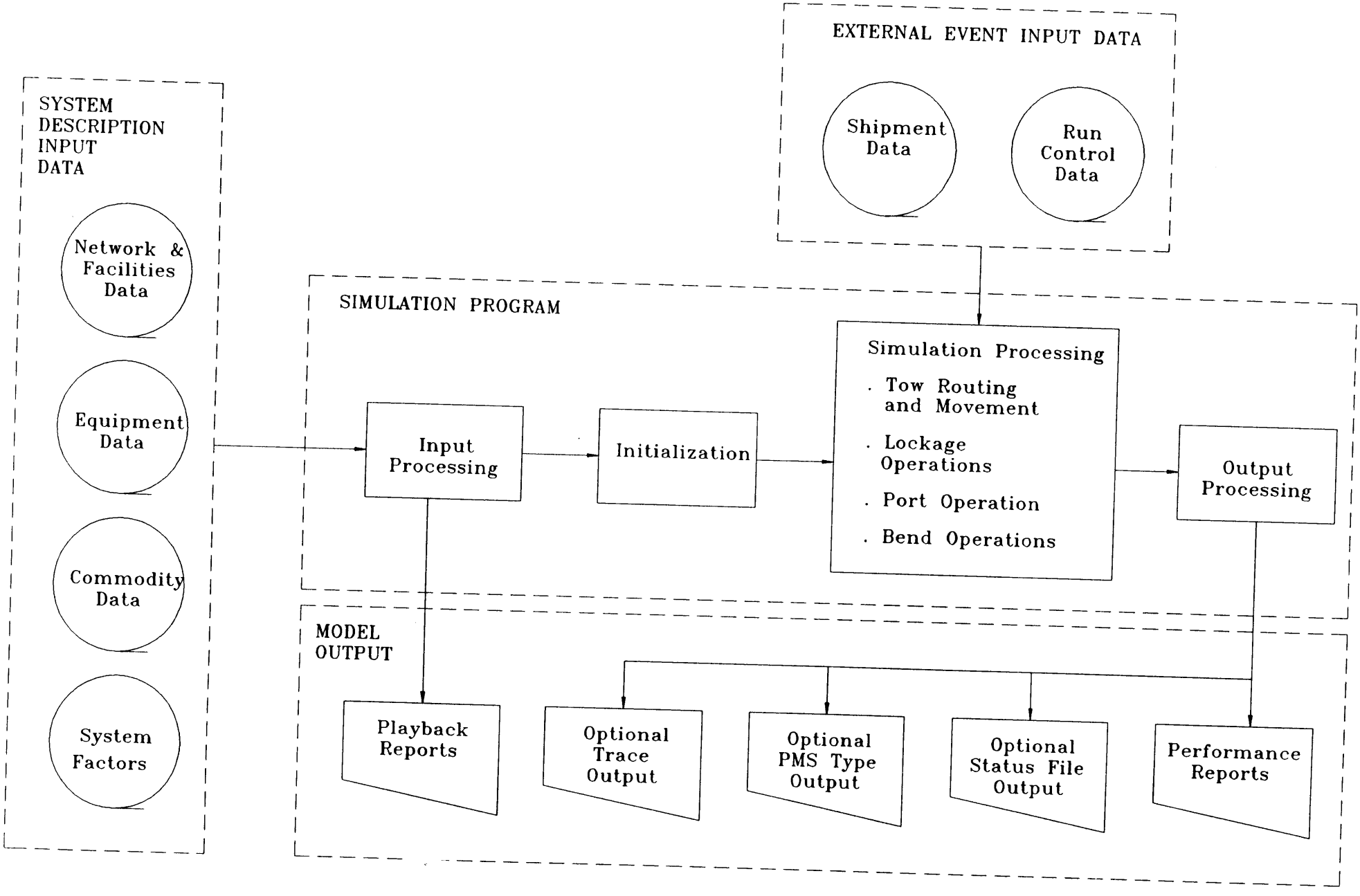


FIGURE 5-1

Each shipment is specified by a shipment origin, shipment destination, net tons, commodity class, time of availability, type of vessel and loaded versus empty designation. The run control records cause such events as the resetting of accumulated statistics, the printing of intermediate output reports, the saving of optional data, and the end of simulation. The lock downtime records cause a specified lock chamber to go out of service, to simulate equipment malfunctions, accidents, weather delays, and so on.

c. Simulation Program

The simulation program is the operational heart of the model. It processes the input data, produces playback reports, initializes the waterway system, processes each shipment from origin to destination, records statistics for generation of performance output reports, and creates files for post-processing by other programs.

d. Output Reports

Playback reports are produced by the input processing routines of the simulation program. These reports echo the system description input data in a convenient format for user data checking. The output processing routines of the program use statistics gathered during the simulation to generate performance reports on lock utilization and delay, vessel utilization, port activity, detailed traffic summaries, and other optional reports specified by the user.

Waterway System Representation

A description of the way in which the various elements of the inland navigation system are presented in this simulation model appears in Appendix 'D'.

The way in which the input definitions were modified for the purpose of the OCCE Study is described in the following section.

SIMULATING OPERATION OF THE PANAMA CANAL

The IW-WAM was used with minor modification to simulate the operation of the Panama Canal for Phase 1 of this study. Various program modifications were made for more accurate simulation in Phase 2. This section focuses on how the model was used in Phase 1, since many of the concepts employed apply to both phases of the study. Subsequent sections take up the Phase 2 modifications.

Waterway Network

The IW-WAM data structure was directly usable, without change, for representing both the existing canal and the proposed alternatives. The system consists of a

port at each end, locks at Gatun, Pedro Miguel, and Miraflores, a bend to represent the Culebra Cut, and the intervening reaches between these elements. The bend data structure is well suited for modeling the navigation restrictions in the Cut, and can be configured to permit only one-way traffic for the appropriate classes of vessels. Ports were used only as locations to initiate and terminate vessel transits, so the cargo loading and unloading data were entered so as not to interfere with this function. Some intermediate ports were added to represent junctions where new channels for the third locks plans would join the present system.

The existing locks are represented as dual chamber facilities, where each lane is considered to be a single chamber. The level of detail available in the Ship Data Bank for lock passage times does not support more detailed modeling of each level at Gatun and Miraflores (which could be represented as successive locks), and the field observations made at those locations indicated that a greater level of detail is not needed.

Configurations with a new third lane of locks can be represented directly as a branch in the network, with the new lock located in this branch. The Phase 1 model requires preassigning vessels to use the new lock. Dynamic assignment of vessels to minimize vessel delays was added to the Phase 2 model.

The alternative sea-level canal configurations were also represented readily. The tide gates included in some systems can be modeled as locks. The downtime event can be used to model periods when the tide gates are closed to vessel traffic, and the times of these events can be obtained from the runs of the LATIS model. Tidal basins impose no particular restrictions on the sea-level canal's network representation. One-way canals operated on a fixed cycle can be modeled with a combination of locks located in new branches to simulate tide gates or traffic control points, and appropriate downtime events to simulate the directional schedule of the single lane channel.

Vessels

The key to representing the Panama Canal vessel fleet was to set up a one-to-one correspondence between commodity class, towboat type, and barge type. The model data structure was modified to allow a user-specified number of vessel classes, replacing the former limit of 15 classes. Up to 22 different vessel types were used in the study. The towboat inputs, which include horsepower, were used to specify the motive power of the vessel, and the barge data to specify its size characteristics. Together, these data are used to estimate vessel speed and the space occupied in a lock chamber, so the data items were specified with these two uses in mind.

The vessel classes used initially were the same as those for which average transit times are maintained separately by the Marine Bureau of the PCC for vessel

scheduling purposes. These classes are defined in Chapter 3. Separate classes were defined for passenger ships and recreational vessels.

Tug boats can be treated as light boats, and are already accommodated in the WAM. Recreational craft can be handled either as a separate vessel class on the shipment list (the method used in this study), or by invoking the lock recreational craft generators that are built into the model.

Release of vessels from their arrival ports into the Canal is controlled by the manner in which the availability time is specified on the shipment list, which is a function of the ship's arrival time at the port and the vessel class. This process occurs externally to the model, and can be structured to observe efficient scheduling practices such as avoiding conflicts in restricted sections or establishing convoys for sea-level canal transits. Most alternative systems simulated include removal of current restrictions, so no special scheduling rules were needed in Phase 1. The lock downtime feature was used to enforce convoy formation for the sea-level canal plans.

Lockage Operations

The IW-WAM provides for input of processing time distributions for fifteen lockage types for each chamber (lane) in each direction, plus distributions related to setover and multi-vessel lockages. The fifteen distributions are intended to correspond to single, double, 3-cut, . . . , 15-cut lockages. For Panama Canal locks, these input fields were used to specify times for the different vessel classes discussed above, and the multi-vessel locking times were used to model tandem lockages. (The setover lockage inputs are available to handle other special situations, but were not used.) In concert with this, the model logic was modified in Phase 1 to change the way in which the lockage type is determined. The revision consisted of specifying the lockage type as part of the towboat class record.

The method of accommodating relay lockages differed between Phases 1 and 2. Relay operations reduce throughput time, and should, therefore, be included for purposes of estimating capacity. On the other hand, it is currently infeasible to relay on all chambers continuously, and the feasibility of relaying on new high lift locks has not yet been fully addressed. For Phase 1, the approach was to conduct most model runs with continuous relaying, so as to estimate maximum capacity. For Phase 2 the model was modified to permit switching into and out of relay operations on a scheduled or demand driven basis.

Channel Operations

The basic channel operation is estimating the vessel's travel speed. Initial trial runs of the model used the model's speed function, with good results. Vessel input data were adjusted to improve the results, and the channel and bend speed coefficients were applied as final adjustments.

The WAM's bend (restricted channel) processing logic is fairly detailed and complicated. In particular, this feature was used to enforce one-way passage of large vessels through the Culebra Cut for the model calibration runs, and for selected Phase 2 runs involving channel restrictions in the Cut.

Simulation Support

The model's input and output routines needed little modification for Phase 1. At worst, some of the labels attached to the output are inappropriate, and require interpretation by the user. Labels were modified for the Phase 2 version to refer specifically to the Panama Canal.

The initialization or warm-up feature was used without change, since it is controlled by input parameters. Since the system can be transited in about eight hours, and given the cyclic nature of present scheduling practices, it was decided that no warm-up was needed, and that the simulations could simply start with the first day's traffic queued at the ports and an otherwise empty system.

WAM MODIFICATIONS, PHASE 2: HIGH-RISE LOCK CANAL

The objective of this part of the study was to modify the WAM to provide for more realistic and accurate simulations and capacity determinations for the status quo and high-rise lock systems. The following sections describe the logic and program modifications that were implemented and tested in Phase 2.

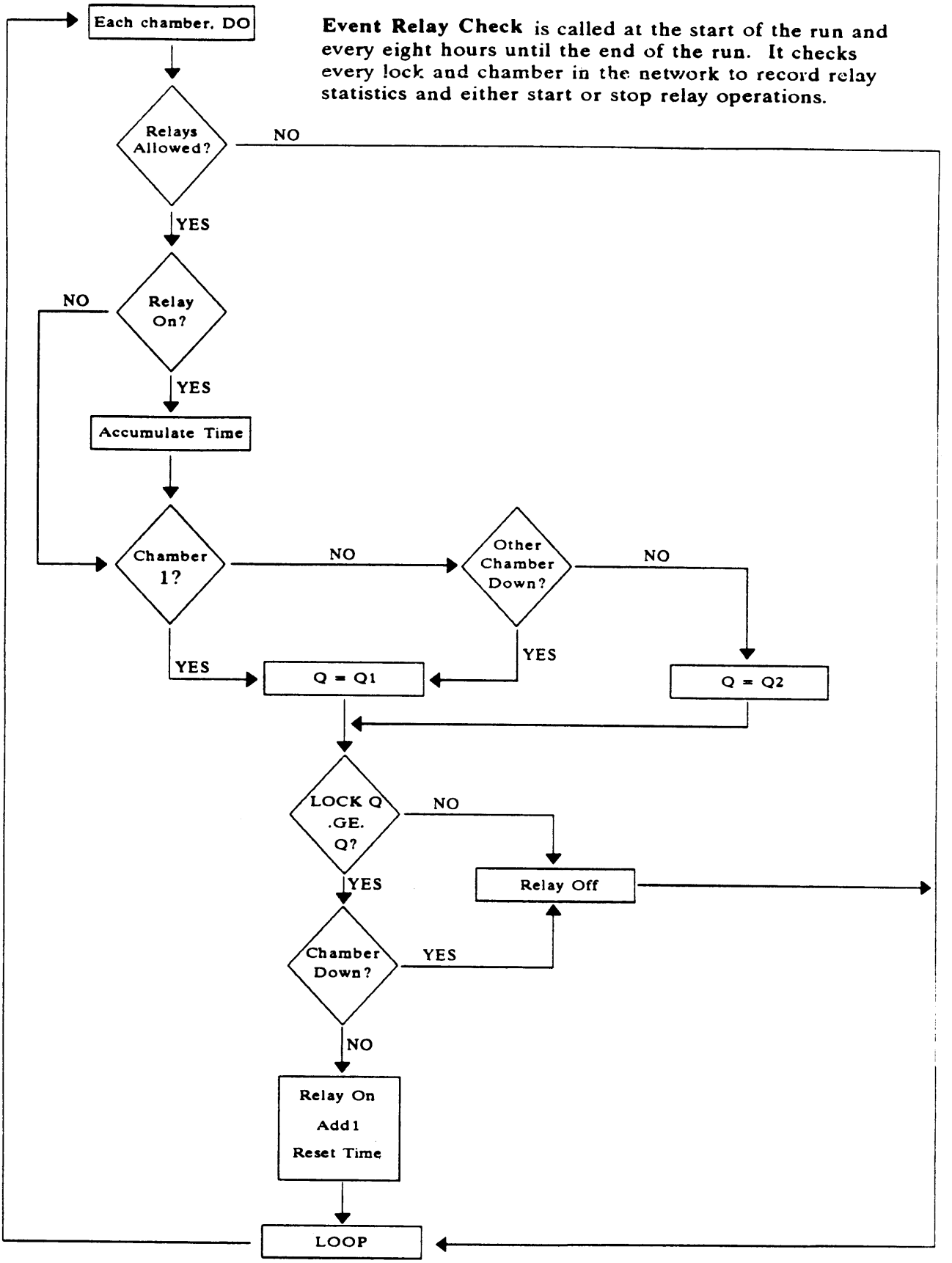
Relay Lockages

Relay operations are now generated internally, based on queue size at the start and end of each eight-hour shift. Additionally, relay operations are started at one lane of dual-lane locks when the other lane is down. This requires additional time distributions and queue size variables in the input data, and model logic to check the current queue size. It also requires a separate relay event generator to start and stop relay operations. Figures 5-2 and 5-3 indicate the logic used in the WAM. Modification of the output report displays, to provide information on the extent of relay utilization, was also accomplished. Items reported include percent utilization by relay and normal lockage time, percent of time in relay mode, and the number of relay shift operations by chamber. Additionally, the percent downtime and number of downtime events by chamber are reported.

Standard Deviation of Queue Length

The WAM was modified to record the sum of queue lengths and the sum of the squares of queue lengths at each lock and bend, by direction and total. Output tables on locks and bends were expanded to include the standard deviation and the actual average queue. Average and standard deviation of queue lengths are

LOGIC FOR RELAY OPERATIONS



Event Relay Check is called at the start of the run and every eight hours until the end of the run. It checks every lock and chamber in the network to record relay statistics and either start or stop relay operations.

FIGURE 5-2

LOGIC FOR RELIEF DURING LANE OUTAGES

Event Downtime was modified to check the relay status of this chamber and other chambers at the lock.

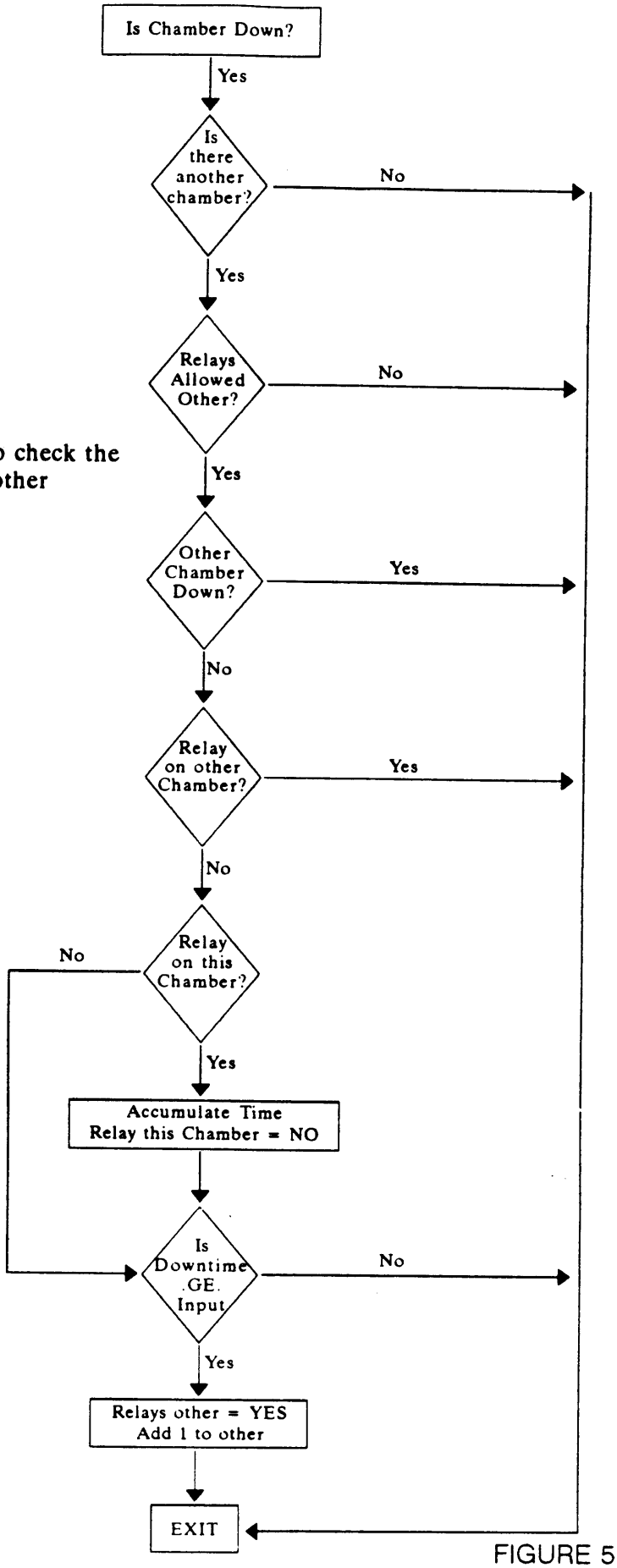


FIGURE 5-3

now recorded from the point of view of the ship, i.e., the queue length encountered upon arrival.

Routing Dynamics

The WAM was modified to include internal decision rules for assigning a ship to the next sector of the network in cases where parallel routings are possible, eg. the third locks plans. The model bases the routing choice on the minimum time to transit the next set of possible sectors divided by the number of available lockage lanes, as indicated in Figure 5-4. A sector bias factor was added to adjust or calibrate the model and a routing switch, which can disable the dynamic routing option, was also added. The estimated minimum time to transit a sector uses the following equations:

- last transit time = transit time of last ship - sector bias;
- minimum time = (ships in sector X last transit time)/lanes;
- minimum time = maximum of minimum time or zero.

Multi-Vessel Lockages

There was some concern that there were too many multi-vessel (tandem) lockages occurring in the preliminary simulation results, especially for the third lock alternatives which feature wider chambers. The model was modified to add a global clearance variable between vessel lengths. Also, the model was changed to prevent vessels from locking side-by-side. Test runs showed a significant reduction in the number of multi-vessel lockages as a result of these changes.

Metric Conversion

This conversion was accomplished in two parts. First, the output reports were modified to display values in metric equivalents. Next, the model was changed to read input values in metric.

Expanded Output

The resource usage file output was expanded to show the route number. The route number is simply the sum of the sector numbers through which a shipment transits. In the OCCE Study, the network descriptions were configured in a way that this number is unique for all possible routes. For example, for the third lock alternatives the route numbers have the following meaning:

19 - Existing Locks;
22 - New Gatun & Existing Miraflores;
21 - Existing Gatun & New Miraflores
24 - New Gatun & New Miraflores.

DYNAMIC ROUTING LOGIC

Routine Junction Stop was modified to dynamically check for the fastest route when a choice of next sectors were possible. Other model routines were modified to dynamically record the number of ships and last transit time through the sector.

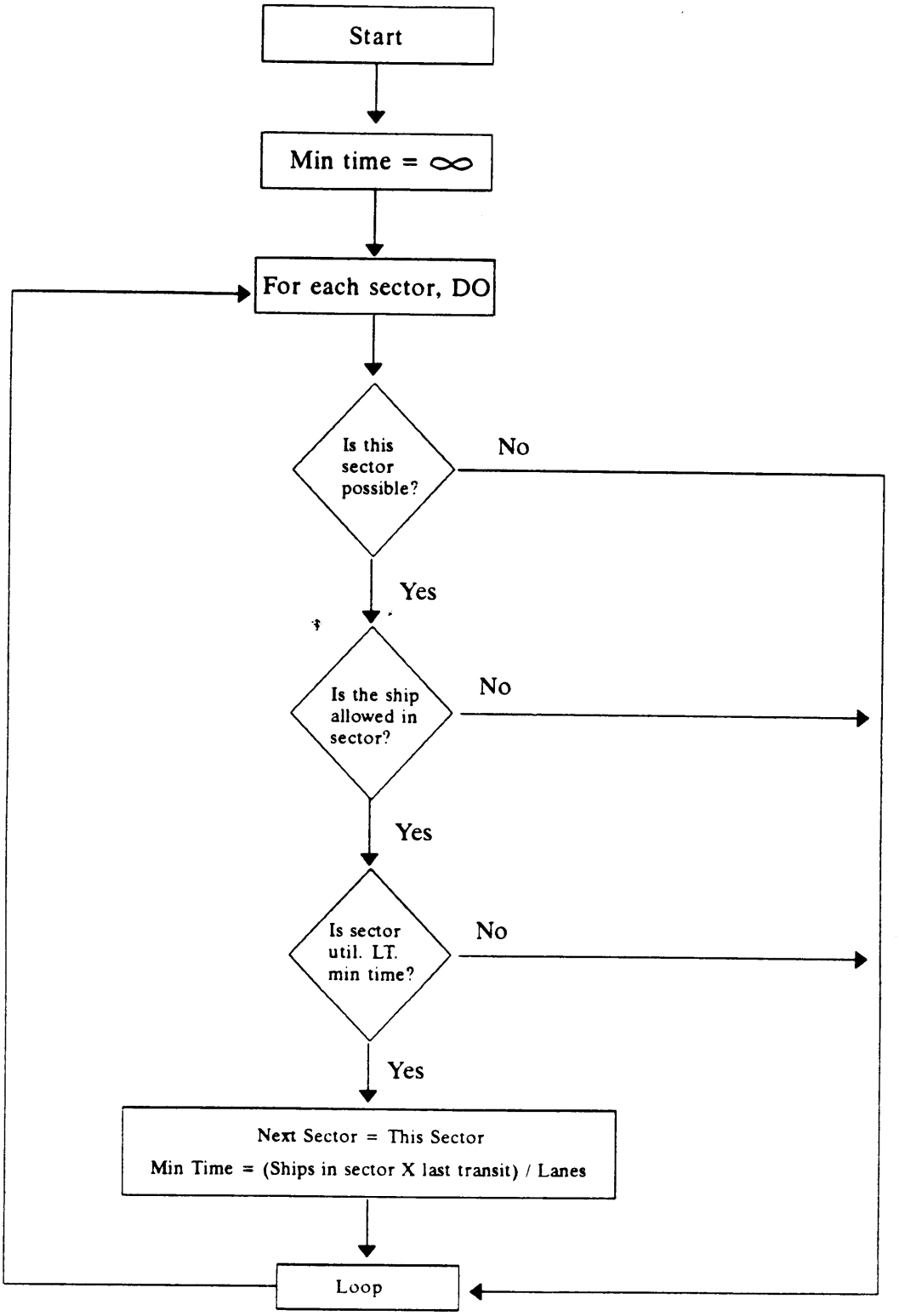


FIGURE 5-4

The Foxpro program post-processor was modified to provide a summary of transit times and delays by route.

WAM MODIFICATIONS, PHASE 2: SEA-LEVEL CANAL

For Phase 2 of the study, the WAM was modified to incorporate new software modules to model the formation and operation of ship convoys through the proposed sea-level options for the Panama Canal. This effort also included the development of algorithms to simulate dynamic ship assignments to alternative routes, including the sea-level and status quo options.

This section presents the model assumptions adopted, the convoy formation process, the dynamic ship assignment logic, and the WAM integration process.

Assumptions

The following are the assumptions adopted to guide the modeling process.

1. The "creation" of each ship is triggered by reading from an ASCII file. This file contains records with information about the ship type, arrival time, and arrival location (Pacific or Atlantic ocean).

2. The model has access to a table that provides ship attributes by ship type. These ship attributes are: ship speed, ship length, and a required ship clearance from any other ship within a convoy.

3. Ship priority is set to "first in - first out" (FIFO) and priority change is not allowed. However, this limitation can be easily modified when priority assignment procedures are known.

4. The dynamic assignment of ships to a convoy located at an alternate route is performed at an imaginary location (dynamic assignment point) where ships are indifferent to the travel distance to canal option entrances. That is, only the difference in expected travel times via the two available routes is considered in the decision process.

5. The tide gates, located at each end of the single-lane section, operate in phase with the tide levels (timing) of the Pacific ocean. The gates and channel operation were described in Chapter 4.

Sea-Level Convoy Formation

The convoy formation for the sea-level option is described by the model as follows:

1. After a ship route assignment for the sea-level route takes place, if a convoy is being formed and has not yet started its transit, the ship

will travel to the anchorage to take its place in the convoy. The first ship of the convoy will time its arrival at the near tide gate at slack tide, a safe interval after the gate is scheduled to open.

The new arrival will position itself behind the last ship ahead, at a distance equal to its "clearance". If there is no waiting queue, and the ship has been cleared for transit, the ship can proceed into the channel and travel at its allowable speed to join the convoy ahead, if any is present.

During convoy travel each ship maintains its position relative to the ship ahead. This approach is structured to take into consideration the delays that might be experienced by the occurrence of unplanned interruptions.

Before a ship "appears" at an open gate, it is determined whether there is enough time, before the tide gate closes, for the ship to enter the channel and completely clear the gate. If there is not enough time, this "last" ship becomes the "first" ship of the next convoy. This tide cycle delay, related to the gate position, would have been taken into consideration when making the dynamic route assignments.

2. The channel operation is simulated for convoys moving from the Pacific to the Atlantic ocean and conversely. The entering convoy waits until the exiting convoy clears by an appropriate time interval before entering the channel.

Dynamic Ship Assignment

Dynamic ship assignment is based on the answer to the following question: How long will it take for a ship to traverse the canal using each of the alternative routes under their present conditions? At the dynamic assignment point, the model performs the following:

1. Given a ship type, the module determines whether it is a large ship which must use the sea-level canal route. If it is, this ship will proceed to join a convoy as described above. If it is not, then the following procedure is followed:

   a. Calculate a base time for the ship to travel the sea-level channel, unimpeded. Calculate (update) the **impedance value**, defined as the delay due to the ships ahead in the convoy (number and type) but not yet in the channel. If the tide gate is closed, it takes into account the delay until the gate opens, as well as the waiting time imposed by other vessels awaiting the opening of the gate. The possibility that the waiting

queues are so long that all the vessels cannot be serviced during the next or the remaining cycle time is also accounted for in these calculations. Add the impedance and the base time to obtain the ship's total travel time.

b. Estimate the delay that the ship would experience if it were to use the status quo canal. This estimate is based on the transit time of the last ship to use the status quo canal.

c. At the routing point and per each routing option, the assignment algorithm continuously updates the travel impedance due to the number and type of ships already present in the system.

d. The route selection is then based on the shortest estimated time to travel among the alternatives selected.

For the options with tidal locks, the single-lane channel requires convoy operations in alternating directions, hence, the same logic applies.

WAM Integration

The new sea-level canal module was integrated with the WAM as follows. As a ship is generated, the WAM processing of that ship is interrupted and the dynamic assignment logic is executed. If the ship is assigned to the status quo canal, its transaction record is released back to the normal WAM event processing routines. However, if the ship is assigned to the sea-level canal appropriate data are transmitted to the sea-level module and the normal WAM shipment record for this ship is destroyed.

MODEL CALIBRATION

The basic data sources and the procedures used to estimate the initial WAM inputs, for Phase 1 of the OCCE Study, are documented in Appendix E. In Phase 2 of the project, new data on ship characteristics were used (see Chapter 6), further analysis of the PCC Ship Data Bank records was performed (see Chapter 3), and the other model inputs were successively refined to produce better agreement of the model outputs with the observed operations of the existing Panama Canal. The results obtained by running the recalibrated WAM with input data representing the existing canal are presented below.

Table 5-1 shows the WAM average locking time outputs and the PCC lockage schedule times. (To produce this comparison, two WAM runs were made, with the model set to use regular lockage times and relay lockage times, respectively.) It is apparent that the scheduled times for relay lockage assume that ships are locking consecutively, and thus full credit for zero locomotive travel time is taken. In the model, the "turnback time" is not counted as part of a vessel's locking time.

TABLE 5-1
WAM CALIBRATION RESULTS COMPARED WITH PCC LOCKING TIME SCHEDULE

Vessel Class	Source*	Average Locking Times (minutes)				
		Gatun Locks		Pedro Miguel Locks	Miraflores Locks	
		Regular	Relay		Regular	Relay
1	PCC	60	30	30	40	30
	WAM	57	33	28	39	31
2	PCC	60	35	30	40	30
	WAM	58	33	30	40	30
3	PCC	60	35	30	45	35
	WAM	59	32	31	45	35
4	PCC	70	40	40	50	40
	WAM	69	44	38	50	40
5	PCC	70	45	40	50	40
	WAM	69	46	39	51	39
6	PCC	70	40	40	55	40
	WAM	72	45	40	54	39
7	PCC	75	45	45	65	45
	WAM	75	46	44	62	45
8	PCC	85	50	50	70	50
	WAM	86	59	50	70	50
9	PCC	70	45	40	60	45
	WAM	73	48	44	61	45
10	PCC	85	50	50	70	50
	WAM	86	66	53	70	54
11	PCC	105	60	60	80	60
	WAM	106	77	61	82	59
12	PCC	125	75	65	90	60
	WAM	133	101	69	90	68
Tandem	PCC	70	40	40	50	40
	WAM	70	42	40	52	39

*PCC = Marine Bureau Scheduling Table
WAM = Waterway Analysis Model Output, 1990 Calibration (Phase 2)

Consequently, to obtain comparable figures, the average locking times output in the calibration run with relay lockage were reduced by 10 and 15 minutes at Miraflores and Gatun, respectively.

The overall level of agreement is quite good, especially for the regular lockage case. The relay lockage times are also in good agreement with the schedule times, with the possible exception of the times for vessel classes 10, 11, and 12 at Gatun. In general, where there are noticeable differences, the simulated average locking time exceeds the schedule time. This is in line with expectations, since the schedule excludes the long locking times that are observed to occur in practice, especially for the larger vessel classes.

Table 5-2 displays the locking times output by WAM along with the values obtained from the SDB records. Recognizing that the SDB values listed are taken from unsmoothed data and include some delay time, the agreement is reasonable. The standard deviations in the WAM results tend to be smaller and more uniform than the SDB standard deviations, indicating that the analytical intent to use more compact distributions than those of the raw data was achieved.

A second major part of the calibration is estimating ship speeds in channels and in the Culebra Cut. Table 5-3 shows the five segments into which the canal system was divided for purposes of analyzing ship travel times and speeds, as explained earlier, and Table 5-4 gives the mean travel speeds for each segment, both from the SDB analysis and as computed by the model. As can be seen in the table, the agreement between the estimated and actual ship speeds is excellent.

Some statistics concerning lock operations recorded in the calibration run are presented in Table 5-5. The lock utilization and delay levels look reasonable. In this run, relay operations were scheduled on demand at Gatun Locks about nine percent of the time during the year, but were needed only two percent of the time at Miraflores. It is recognized that the actual schedule of relay lockage periods at Miraflores would more closely resemble the schedule at Gatun; the model results merely reflect the lower service time at Miraflores. The high downtime at Pedro Miguel is due to the practice of shutting down one lane at night. The low delays experienced at this location confirm that this practice does not adversely affect the service capacity of the system.

Table 5-6 provides the same statistics as in Table 5-5, but for the calibration run with 100% relay lockage. It is interesting to note that this extremely high usage of relay lockages produces an average delay savings of only about one hour per vessel. This result confirms the appropriateness of allowing the model to schedule relay lockage operations as needed in the runs to simulate the study cases.

TABLE 5-2
WAM CALIBRATION RESULTS COMPARED WITH SDB LOCKING TIMES

Vessel Class	Source*	Northbound Locking Times (minutes)					
		Gatun Locks		Pedro Miguel Locks		Miraflores Locks	
		Average	SD	Average	SD	Average	SD
1	SDB	79	21	34	28	51	13
	WAM	60	16	26	7.7	40	8.7
2	SDB	76	17	33	9.7	48	8.0
	WAM	61	17	29	7.5	40	9.0
3	SDB	76	18	34	9.6	50	11
	WAM	59	17	29	6.9	45	9.1
4	SDB	81	21	36	21	52	9.5
	WAM	70	17	36	6.6	50	8.8
5	SDB	86	17	38	5.5	56	6.9
	WAM	70	16	37	7.1	52	8.7
6	SDB	86	21	41	18	55	10
	WAM	71	19	41	9.1	53	9.9
7	SDB	91	19	42	13	58	7.8
	WAM	75	20	45	10	61	9.1
8	SDB	95	18	48	22	63	9.1
	WAM	87	20	50	9.3	70	9.8
9	SDB	93	21	45	18	61	9.1
	WAM	73	19	45	12	60	8.8
10	SDB	101	21	49	16	67	10
	WAM	88	18	54	12	71	11
11	SDB	-	-	-	-	-	-
	WAM	110	18	64	16	83	12
12	SDB	118	23	61	13	85	11
	WAM	127	22	73	14	94	11

*SDB = Marine Bureau Scheduling Table
WAM = Waterway Analysis Model Output, 1990 Calibration (Phase 2)

TABLE 5-2
WAM CALIBRATION RESULTS COMPARED WITH SDB LOCKING TIMES

Vessel Class	Source*	Southbound Locking Times (minutes)					
		Gatun Locks		Pedro Miguel Locks		Miraflores Locks	
		Average	SD	Average	SD	Average	SD
1	SDB	70	13	36	13	51	14
	WAM	54	14	29	7.8	39	9.3
2	SDB	70	14	36	13	49	9.9
	WAM	54	14	31	8.0	40	9.4
3	SDB	71	14	36	14	50	10
	WAM	54	14	32	7.5	44	9.3
4	SDB	75	15	38	12	53	12
	WAM	64	13	39	8.9	50	9.4
5	SDB	77	14	44	16	51	9.2
	WAM	63	11	39	7.6	50	11
6	SDB	79	15	41	12	56	15
	WAM	67	17	40	9.2	53	12
7	SDB	86	19	42	10	60	16
	WAM	68	15	43	10	60	12
8	SDB	92	16	45	8.7	62	15
	WAM	82	17	51	9.3	71	11
9	SDB	87	11	42	11	62	15
	WAM	67	17	42	9.0	58	13
10	SDB	93	13	47	9.9	65	14
	WAM	83	18	51	9.7	70	14
11	SDB	102	17	49	7.4	69	15
	WAM	101	20	60	9.0	78	14
12	SDB	124	19	56	10	77	14
	WAM	133	20	67	10	87	14

*SDB = Marine Bureau Scheduling Table
WAM = Waterway Analysis Model Output, 1990 Calibration (Phase 2)

TABLE 5-3
SDB TRANSIT TIME SEGMENTS

		Miles	Km
1	Atlantic Approach	9.3	14.9
2	Gatun Lake	21.9	35.3
3	Culebra Cut	10.9	17.5
4	Miraflores Lake	2.0	3.3
5	Pacific Approach	7.7	12.4
		51.8	83.4

TABLE 5-4
SHIP SPEEDS: WAM CALIBRATION VS. SDB DATA

Segment		SDB Mean	WAM Mean	WAM Std. Dev.
Atlantic Approach	NB	14.7	14.7	1.87
	SB	8.1	8.3	1.06
Gatun Lake	NB	7.0	6.9	0.92
	SB	9.8	9.9	1.33
Culebra Cut	NB	10.2	10.2	1.55
	SB	9.3	9.3	1.38
Miraflores Lake	NB	5.7	5.7	0.73
	SB	5.5	5.5	0.71
Pacific Approach	NB	6.1	6.1	0.79
	SB	9.3	9.3	1.20

Note: All speeds are expressed in units of statute miles per hour.

TABLE 5-5
CALIBRATION RUN - SDB SHIPS

Lock	Ships	Average Lockage (hour)	Average Delay (hour)	Lock Utilization (%)	Relay Operations (%)	Down Time (%)
Gatun	12,106	1.19	1.95	75	8.9	5.4
Pedro Miguel	12,110	0.66	0.28	44	0.0	11.6
Miraflores	12,108	0.89	0.28	59	1.7	1.4

TABLE 5-6
CALIBRATION RUN - 100% RELAY LOCKAGE

Lock	Ships	Average Lockage (hour)	Average Delay (hour)	Lock Utilization (%)	Relay Operations (%)	Down Time (%)
Gatun	12,106	1.03	1.03	65	92.7	5.1
Pedro Miguel	12,109	0.66	0.21	43	0.0	11.3
Miraflores	12,109	0.85	0.19	56	97.7	1.1

The overall average ship transit times (hours) in this run are given in Table 5-7. As indicated, the match with the transit time results from analysis of the SDB records is relatively good. Combining the average travel time of 12 hours with the average of about 8 hours of schedule delay experienced in 1990 indicates that the simulated time in canal waters (TICW) is about 20 hours, which is quite close to the 19 hours estimated from the SDB data. Both the simulated and actual TICW values are under the PCC standard of 24 hours by only a small margin. This matches the information obtained during the visits of the research team to Panama.

TABLE 5-7
CALIBRATION RUN - SDB SHIPS
(Average Travel and Delay Times (Hours)

	North	South	Average
Travel	6.56	5.69	6.10
Lockage	2.70	2.77	2.74
Lock Delay	2.57	2.46	2.51
Cut Delay	0.64	0.25	0.43
Total	12.47	11.17	11.78
SDB Data			
Travel	12.5	9.8	11.1
Udy - Ready	7.8	7.9	7.9
TICW	20.3	17.7	19.0

In summary, the model calibration was deemed to be good enough to proceed with the simulation of the alternative conceptual plans.

CHAPTER 6

PREPARATION OF SIMULATION

The starting point for the Phase 2 simulations was the set of network and down-time files produced during Phase 1. The procedures used to prepare these files are outlined in Appendix E. The additional analyses of the Ship Data Bank (SDB) records conducted to refine the model inputs are documented in Chapter 3 herein. The additional data, assumptions and procedures used to obtain the final results are outlined hereinafter.

VESSEL MIX FORECASTS

In accordance with a directive from CAS dated November 11, 1992, the analyses herein are based on the Phase 1 vessel mix forecasts prepared by the CTP contractor (WEFA), for maximum vessel sizes of 65,000, 150,000 and 250,000 DWT (see Appendix F). The vessel mix for a maximum vessel of 200,000 DWT was interpolated by TAMS from the results of the 150,000 and 250,000 DWT mixes.

The estimates assumed that the Phase 1 data for the 250,000 DWT category would be applicable, except that for years 2020 and 2060, Ballast Southbound and Laden Northbound, the data for ship size range 150,000 to 249,999 DWT would apply to ship size range 150,000 to 199,999 DWT, and the data for ship size range 250,000 to 299,999 would be eliminated. The resultant estimates are shown in Table 6-1.

TABLE 6-1
VESSEL MIX FORECASTS
(number of transits)

	Ballast		Laden		All		
Year: Case	North	South	North	South	North	South	All
1990 : 1	676	1,084	4,806	4,956	5,482	6,040	11,521
2020 : 1	1,043	1,790	7,684	7,833	8,727	9,623	18,350
2020 : 2	1,075	1,757	7,353	7,958	8,428	9,715	18,143
2020 : 3	1,080	1,756	7,351	7,986	8,431	9,742	18,173
2020 : 4	1,088	1,756	7,351	8,028	8,439	9,784	18,223
2060 : 1	1,349	2,197	9,967	11,193	11,315	13,497	24,812
2060 : 2	1,384	2,168	9,652	11,296	11,037	13,630	24,667
2060 : 3	1,366	2,167	9,650	11,190	11,016	13,357	24,373
2060 : 4	1,374	2,167	9,650	11,230	11,049	13,692	24,741

1: 65,000 DWT Design Ship 3: 200,000 DWT Design Ship
2: 150,000 DWT Design Ship 4: 250,000 DWT Design Ship
Source: Cases 1, 2 & 4 - WEFA Phase 1; Case 3 - TAMS, based on WEFA Phase 1

VESSEL CONFIGURATIONS AND CHARACTERISTICS

A range of commercial ships built worldwide in recent years has been reviewed. Ship data reviewed included ships recently built by leading shipbuilders and also those described in typical ship design books (e.g., SHIP DESIGN AND CONSTRUCTION, R. Taggart, SNAME and COMMERCIAL SHIP DESIGN FUNDAMENTALS, Shibata et al, Seizando). During the last four decades, we have seen a rapid increase in ship size, in particular in the tanker and bulk carrier design. A major portion of total volume of commercial ships worldwide are occupied by tankers and bulk carriers. Accordingly, large size ships examined here for this study are mainly tankers and bulk carries. On the basis of these data, the most representative vessel design configurations were determined for this study, including the 12 vessel classes defined in the PCC Ship Data Bank (SDB) shown in Table 6-2.

TABLE 6-2
PCC SDB VESSEL CLASSES

Vessel Class	Beam (ft)	Draft (ft)
1	< 60	
2	60 - 70	
3	70 - 80	
4	80 - 90	< 36
5	80 - 90	> 36
6	90 - 100	< 30
7	90 - 100	30 - 36
8	90 - 100	> 36
9	100+	< 36
10	100+	30 - 36
11	100+	36 - 38
12	100+	> 38

Typical design configurations for the above classes, laden and in-ballast, are shown in Table 6-3.

The configurations and characteristics of large vessels, including 100,000, 150,000, 200,000 and 250,000 DWT were also considered, as indicated hereinafter.

NOTE: Analyses of ship characteristics and behavior, as well as ship-generated waves (Chapter 8) were conducted by Prof. Haruzo Eda, Ph.d. of the U.S. Merchant Marine Academy, Kings Point, NY.

TABLE 6-3
VESSEL DESIGN CONFIGURATIONS FOR CLASSES 1 THROUGH 12

No.	Type	Load	HP	DWT (summer)	Length (m)	Beam (m)	Draft Max. (m)	Block Coeffi-cient [Cb]	Sea Speed (kts) Max.	Sea Speed (kts) Avg.
1	Geo Survey Ship	Laden	7,200	3,100	89.00	15.54	5.49	0.56	17.1	16.8
		Ballast						0.55	17.6	17.4
2	Chemical Carrier	Laden	6,900	12,220	128.92	20.12	8.53	0.76	14.0	13.8
		Ballast						0.72	15.0	14.8
3	22K Bulk Carrier	Laden	7,000	22,000	152.09	22.86	9.75	0.79	13.9	13.7
		Ballast						0.77	14.9	14.7
4	34K Bulk Carrier	Laden	10,800	34,000	167.94	27.13	10.67	0.79	14.5	14.3
		Ballast						0.77	15.5	15.3
5	35K Bulk Carrier	Laden	11,300	36,000	168.24	27.13	11.28	0.80	14.5	14.3
		Ballast						0.78	15.5	15.3
6	Car Carrier	Laden	8,740	9,400	158.79	27.74	7.92	0.55	17.3	17.1
		Ballast						0.51	18.3	18.1
7	29K Bulk Carrier	Laden	7,500	29,000	170.07	27.43	10.06	0.79	14.1	13.9
		Ballast						0.76	15.1	14.9
8	45K Bulk Carrier	Laden	13,000	45,000	201.77	30.17	11.58	0.81	15.5	15.2
		Ballast						0.78	16.5	16.2
9	Car Carrier	Laden	14,700	15,396	199.94	32.31	8.84	0.58	18.0	17.8
		Ballast						0.52	19.0	18.8
10	44K Bulk Carrier	Laden	16,800	44,000	196.28	30.78	10.06	0.81	15.7	15.5
		Ballast						0.79	16.7	16.5
11	60K Tanker	Laden	14,000	60,000	218.84	32.31	11.58	0.81	15.7	15.5
		Ballast						0.79	16.5	16.2
12	66K Tanker	Laden	14,400	66,000	223.71	32.31	12.19	0.81	14.6	14.4
		Ballast						0.79	15.6	15.4

COMPUTER-AIDED ANALYSIS

Computer-aided analyses were made to determine the following parameters of ship operations during canal transit:

1) average and maximum allowable speed;
2) required stopping distance and minimum spacing of ships;
3) requirements for tug assistance.

To establish these parameters, ship operations in a range of canal configurations were examined utilizing data available on the ship stopping behavior obtained from ship trial runs and simulation runs.

An example of stopping data for a fully loaded 38,000 DWT tanker obtained from ship trial runs and also simulation runs are shown in Figure 6-1, which shows an encouraging correlation between ship trial data and simulation results. This particular stopping maneuver was done at a full-sea-speed (16 Knots) under full-load condition in open water. Although actual ship stopping data in a channel were not available, having achieved good correlation between simulated and actual ship stopping behavior, at sea, the simulation analysis was then extended to the case of stopping in a channel at lower speeds. Such an extension of simulation analysis from one speed to another was possible, because speed effects on ship hydrodynamics are well known within a range of speeds under consideration. Accordingly, when the stopping simulation model gives realistic stopping behavior as shown in the above example, it is expected that a simulation run done on the same model at 7 knot initial speed should produce similar realistic stopping behaviors. During the course of the studies, the numerous stopping-models of similar ship configurations previously developed were fully utilized. Results obtained in these similar stopping-models were used to determine stopping distance at 7 knots. Through this procedure, stopping distance predictions for all ship configurations were done in a fairly accurate manner.

When stopping behavior is examined for a wide range of ship size (e.g., from 20K to 250K DWT), the change in available horsepower per ton has to be considered. For a given ship type (e.g., for tanker configurations), a tendency exists for a reduction in horsepower per ton with an increase in ship size. This tendency is shown below and in Figure 6-2. Horsepower predictions shown below and in the figure were determined in a computer-aided manner reflecting data of actual ships built in recent years.

Ship Size:	45K DWT	60K DWT	250K DWT
Engine HP:	12,000	13,000	33,500
Speed	16 knots	16 knots	16 knots
HP / DWT:	0.27	0.21	0.13

STOPPING SHIP TRIAL DATA OF A 38,000 DWT TANKER WITH SIMULATION RESULTS

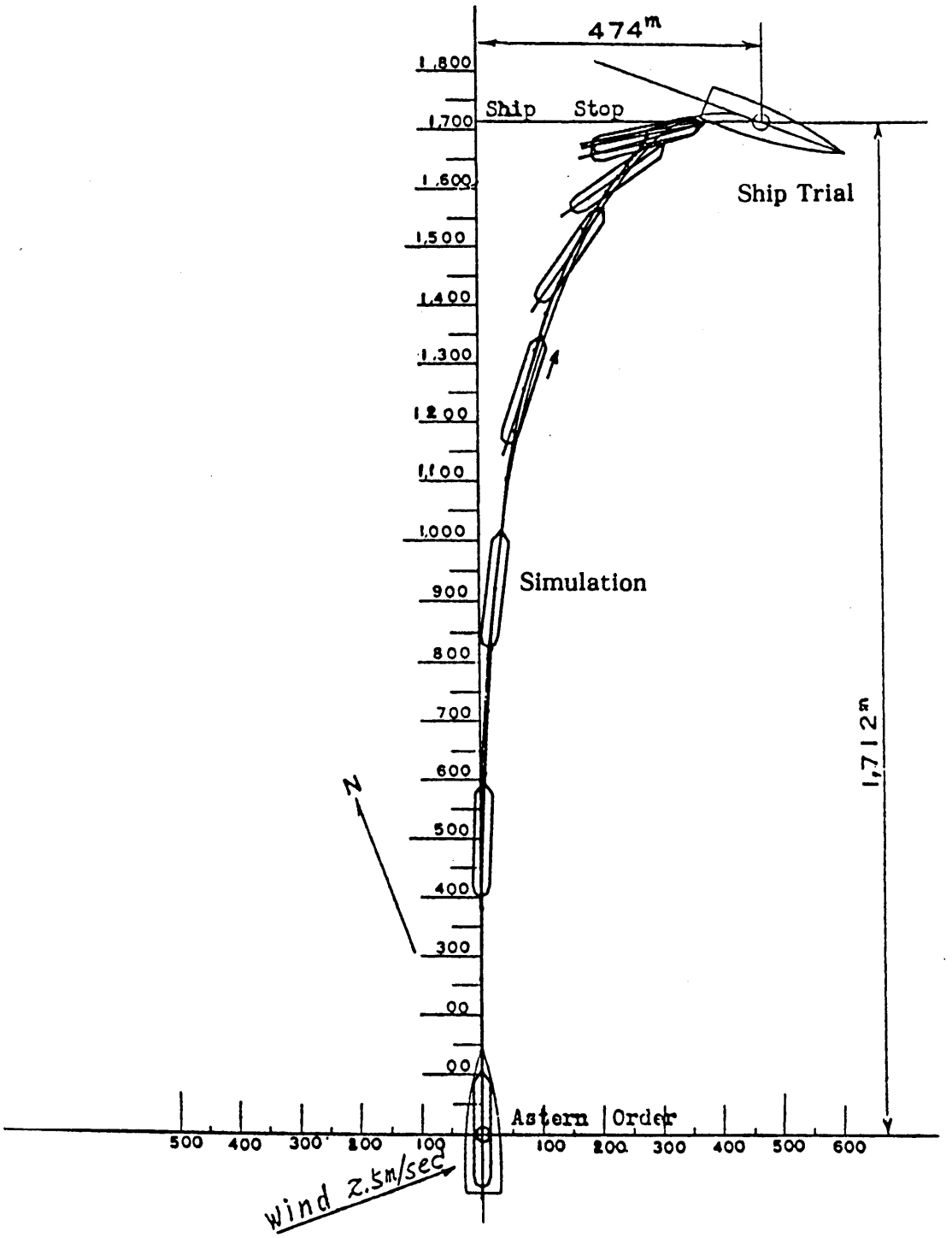


FIGURE 6-1

ENGINE HORSEPOWER FOR A RANGE OF SHIP SIZES
(Computer-Predictions Reflecting Actual Ship Data)

Ship Size	DWT		
	45,000	61,000	250,000
Length bp (ft)	623	646	1,055
Beam (ft)	98	106	174
Draft (ft)	38	40	72
Depth (ft)	52	63	97
Length/Beam	6.4	6.1	6.1
Length/Draft	16.4	16.2	14.7
Beam/Draft	2.6	2.7	2.4
Block Coefficient	0.8	0.8	0.8
Displacement (LT)	54,000	64,000	307,000
Speed (kt)	16	16	16
Froude No. (F_n)	0.18	0.18	0.14
HP	12,000	13,000	33,500

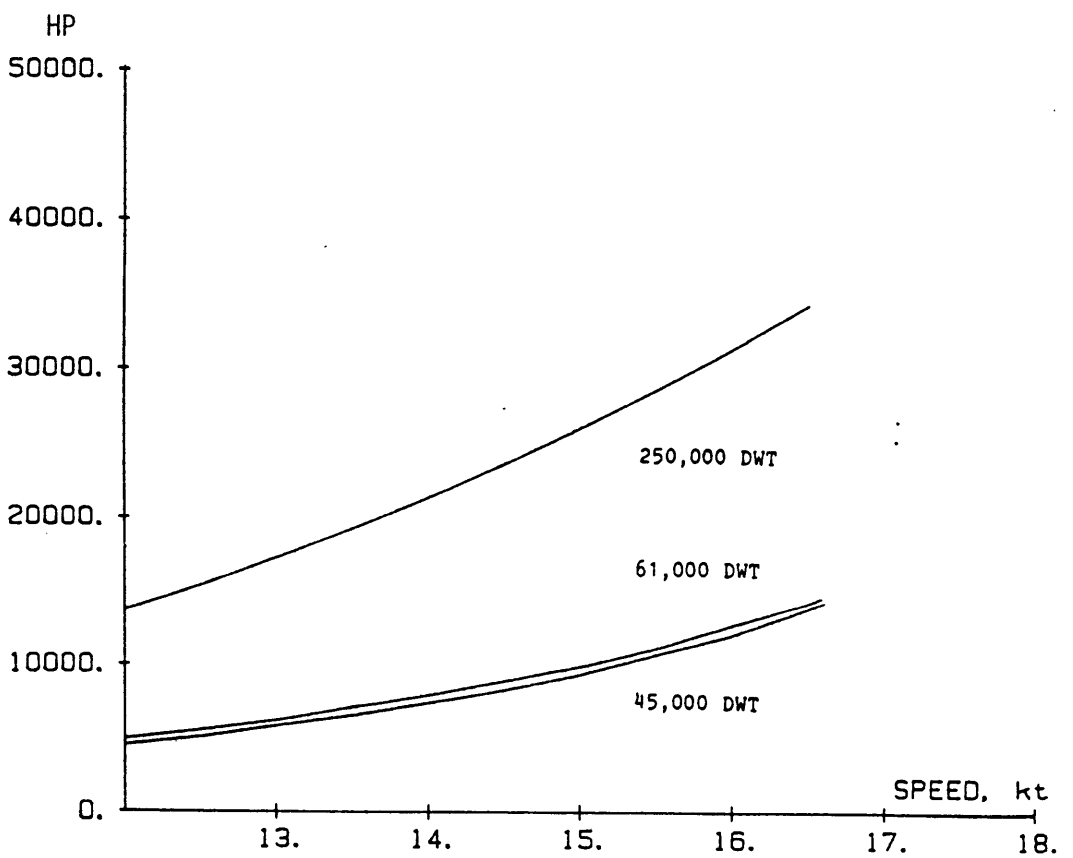


FIGURE 6-2

TABLE 6–4
SHIP SPEED, STOPPING DISTANCE, SHIP SPACING AND TUG REQUIREMENTS

Ship	Type	Load	HP	DWT (summer)	Length (m)	Beam (m)	Draft Max. (m)	Block Coeffi-cient [Cb]	Sea Speed (kts) Max.	Sea Speed (kts) Avg.	Average Speed in Canal (Kts)	Minimum Spacing (m)	Stopping Distance at 7 Kts (m)	No. of Tugs Req'd.
20K	Tanker	Laden	12,000	27,000	186.53	24.99	9.75	0.75	16.4	16.2	6.5	776.29	517.53	0
		Ballast					5.48	0.73	17.4	17.2	6.5	570.56	380.37	0
35K	Tanker	Laden	12,000	38,000	181.96	27.43	11.5	0.82	16.0	15.7	6.5	791.53	527.58	0
		Ballast					6.40	0.79	17.0	16.7	6.5	582.14	387.99	0
45K	Bulk Carrier	Laden	13,000	45,000	201.77	30.17	11.5	0.81	15.5	15.2	6.5	897.90	598.60	0
		Ballast					6.40	0.78	16.5	16.2	6.5	660.16	440.11	0
65K	Tanker	Laden	14,500	61,000	206.95	32.31	13.7	0.81	15.5	15.2	6.5	961.90	641.27	0
		Ballast					7.61	0.79	16.5	16.2	6.5	706.80	471.20	0
100K	Bulk Carrier	Laden	15,000	120,000	249.92	45.11	16.1	0.81	14.0	13.7	6.5	1,290.16	860.10	0
		Ballast					8.83	0.79	15.0	14.7	6.5	948.19	632.12	0
150K	Tanker	Laden	15,650	146,270	274.31	43.28	16.7	0.81	14.0	13.7	6.5	1,463.58	975.62	1
		Ballast					9.14	0.79	15.0	14.7	6.5	1,075.89	717.16	0
200K	Bulk Carrier	Laden	15,600	201,200	298.69	49.98	18.5	0.82	12.0	11.7	6.5	1,684.85	1,123.13	2
		Ballast					10.3	0.80	13.2	13.0	6.5	1,238.65	825.66	1
250K	Tanker	Laden	23,640	258,000	330.08	60.04	19.5	0.82	14.0	13.7	6.5	1,948.49	1,298.99	2
		Ballast					10.6	0.80	15.0	14.7	6.5	1,431.88	954.59	1

Since horsepower per ton is less with an increase in ship size, stopping distance is slightly longer for a larger ship.

Reflecting the ship stopping behavior data obtained in ship trials and simulation runs, stopping distance was estimated and shown in Table 6-4 for typical ships of 20K, 35K, 45K, 65K, 100K, 150K, 200K, and 250K DWT.

Stopping distance increases, of course, with an increase in loading, because there is less power per ton available under a greater loading condition. When a current exists in a channel, the magnitude and direction of current also has a direct impact on stopping distance.

Finally, ship spacing in a channel is a function of many variables, such as ship speed, loading, currents, tug assistance, and reaction time of the human-ship system. The figures in Table 6-4 include an allowance for such factors.

The vessel data above were used to modify the Phase 1 values of the ship characteristics (length, beam, draft, horsepower, block coefficient) of the class 1 through class 14 vessels, derived from the SDB records. The vessel speeds computed by the WAM speed function required only minimal adjustment with the model's speed coefficients, so the revised vessel data were judged to be acceptable.

The estimates of the required ship separations in a sea-level canal, based on stopping distance simulations provided in the above table are based on emergency, full-astern stops. These separations, expressed in feet, were converted to minutes of travel time, then increased to reflect less severe stopping maneuvers and to provide a safety margin, and the resulting values were smoothed. The minimum ship separations so derived are given in Table 6-5.

TABLE 6-5
SHIP SPACING DATA FOR SEA-LEVEL CANAL

Ship Class	Min Spacing (min.)	Ship Class	Min Spacing (min.)
1	6.0	11	12.5
2	6.0	12	12.5
3	6.0	13	7.5
4	6.0	14	6.0
5	6.0	15	12.5
6	7.5	16	15.0
7	7.5	17	14.0
8	7.5	18	17.5
9	9.0	19	15.0
10	12.0	20	20.0

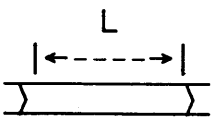
LOCK CHAMBER SIZE

Our field observations in Panama in connection with the OCCE Study indicate that entry and exit times escalate sharply when the ships' beam is within 10% of the lock width and the draft is within 10% of the lock depth.

Accordingly, it is suggested that lock dimensions be 10% greater than each critical dimension for each of the Phase II design ships, with an additional allowance of 30 meters in lock length to allow a tugboat to accompany the ship; as follows:

Design Ship (meters)				Lock Dimensions (meters)		
DWT	Length	Beam	Draft	Length	Width	Depth
150K	305.6	45.9	17.9	365	50	20.0
200K	332.7	50.2	19.4	395	55	21.5
250K	355.5	53.7	20.7	420	60	23.0

The lock length (L) is measured from the tip to the pintel of miter gates, as follows:



LOCKING TIMES

Locking times were modified to produce better agreement with the SDB data. As indicated in Chapter 5, the calibration of the model was found to be satisfactory, so these times were used for all subsequent runs.

LOCK DOWNTIME

The Phase 1 downtime files were augmented with a set of lock outages developed to simulate the occurrence of fog in the Culebra Cut. The probability of fog occurrence and the distribution of onset and duration times were taken from the historical record given in the publication The Panama Canal Pilot. Fog events were generated randomly, and introduced into the downtimes for Pedro Miguel Lock, and for a "dummy" lock placed at the head of the Cut to shut off Southbound traffic (the "locking times" for this lock are all zero, so it causes no simulated delays when there is no fog). Fog occurs primarily in the months of October through December; a sensitivity analysis indicated that the incidence is not sufficiently widespread to impact significantly on capacity.

SIMULATION OF ALTERNATIVE SYSTEMS

Status Quo

The status quo simulations for Phases 1 and 2 were carried out essentially in the same manner. The ship transits were generated for two different ship mixes, based on the WEFA 2020 and 2060 forecasts. Separate runs were made for each ship mix at two different traffic levels, to provide the data points needed for the delay curves.

High-Rise Canal

New channels were defined for the third locks. All channels which would be traversed by the larger ships were modified to provide minimum depths consistent with the drafts of the design vessels. The lock dimensions specified herein were used for the new locks. The level of Gatun Lake was set at 25.9m (85-ft), vs the 27.4m (90-ft) elevation used in Phase 1. The restrictions on large ships transiting the Culebra Cut at night were removed, as was done in Phase 1, except as necessary to reflect fog conditions.

The system configuration for the high-rise cases contains a 0.4 mile area where crossing maneuvers will be required. A run at year 2060 traffic levels of about 24,000 ships required all of the ships to traverse this area. At average ship speeds of around 10 mph, the average time a ship occupies this area is less than 5 minutes. On the other hand, the average ship interarrival interval is 21.9 minutes. Thus, the average traffic intensity in this area is 0.23, which is not high enough to cause significant delays. Even if the occupancy time were to be as high as 10 minutes, traffic intensity would only double to 0.46. Thus, a simulation of this area would produce no interesting results. In cases 6 and 7, queuing occurs here for some ships awaiting access to the single-lane Cut. These ships wait no more than 30 minutes on the average, so some ships could take advantage of this delay to execute any required crossing maneuvers.

Locking times at the new locks were derived from the input distributions for the existing Miraflores Locks. However, recognizing the greater clearances available between the vessel and the lock chambers, the maximum locking time used was that for a class 7 vessel, which has similar clearance in the existing locks. A smooth distribution of locking times from class 1 to class 7 was developed and applied to the range of ship sizes that would use the new locks. This is a significant departure from the Phase 1 procedure, where it was assumed that vessel clearances would be much smaller.

Sea-Level Canal

The sea-level canal was modeled as a separate channel in parallel with the status quo system. The Route 10 case was assumed, with a total length, including the

lengths of the approach channels, of approximately 90 km. All cases featured dual lane approaches and a single lane canal section, and positive tidal current control with either tide gates or tidal locks.

The following cases were modeled:

- 8 single lane, 40 km between tide gates, 6.25 hour cycle, 13.0 km/hr ship speed;
- 9 & 10 single lane, 51.5 km canal section, Pacific locks, three or four parallel chambers, 12.5-hour cycle, 13.0 km/hr ship speed.
- 9a Same as 9 & 10, with three Pacific Locks, except that two chambers are in tandem and one is parallel to the tandem chambers.
- 8a Same as 8, except that a single lane channel (rather than two lanes) would be used from the Atlantic end to the north tide gate.
- 9b Same as 9, except that only a single chamber lock (rather than three) would be used at the Pacific end.

The Pacific locks were modeled with locking times selected to produce an average service time of 45 minutes per ship per lock chamber (i.e., the three-chamber system has a service rate of four ships per hour). Downtimes were borrowed from the event files for the existing Pedro Miguel and Miraflores locks.

SIMULATION RUNS

For the combined status quo and high-rise or sea-level canal runs, dynamic routing was used to assign ships to alternative routes. In this procedure the model assesses the expected transit time (including waiting time) via each available route, and assigns a ship so as to minimize its travel time. Also, all runs featured automatic switching into and out of relay operating mode at all multiple lift locks, as explained in Chapter 5. The queue lengths to trigger relay operations were set to four ships for relaying on one lane and eight ships for relaying on two lanes. Also, whenever one lane experiences an outage exceeding two hours, relaying operations commence on the functioning lane.

Based on data furnished by YEC, the bottom widths of all single-lane and two-lane channels were set at 3.5 times and 7.0 times, respectively, the beam of the design ship.

CHAPTER 7

CAPACITY OF ALTERNATIVE ROUTES

The capacity of a canal alternative is a function of delay or transit time (travel plus delay). A higher capacity can be achieved at a cost of longer delays and greater congestion. The level of delay is a function of the rate of ship arrivals, compared with the rate of ship transits. Delays and transit time increase gradually at low traffic volumes but accelerate rapidly as traffic continues to build. The relationship is characterized by a hyperbolic curve. Capacity of an alternative is actually estimated as the number of ships that can transit the canal at an acceptable delay or transit time. For additional details on capacity curves, see Appendix H.

STATUS QUO AND HIGH-RISE LOCKS CASES

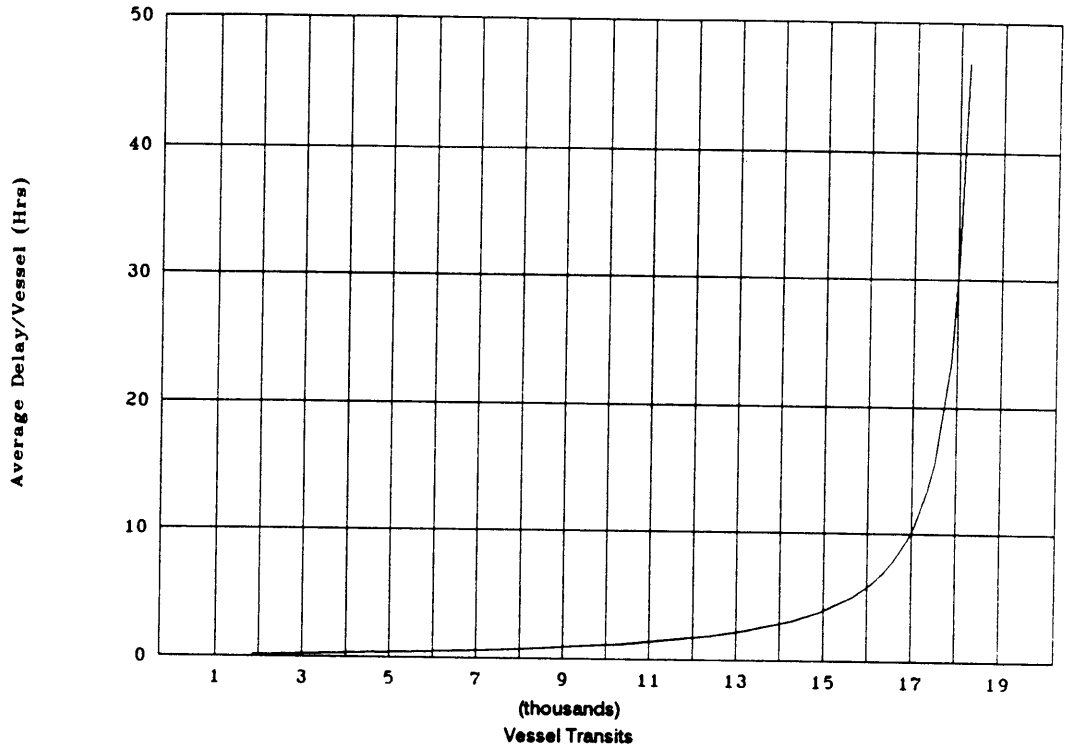
Based on research related to queuing theory, the curves for the high-rise lock alternatives were plotted from two data points, one on the flat leg of the curve and one approaching the vertical (in practice, it is difficult to select a point on the vertical leg because delays approach infinity within a relatively small range of vessel transits). Average delay times of six hours and, alternatively, 10 hours were assumed as the basis of capacity for the high-rise canal cases.

For the High-Rise Canal cases with a two-lane Culebra Cut, the model schedules vessels to begin transit immediately upon arrival. For the single-lane Culebra Cut cases, however, large ships arriving at night do not start their transit until early morning, using the logic outlined in Chapter 3. This waiting time, or ships' scheduled delay, was added to transit delay that results from congestion, to arrive at a total delay. A summary of the simulation results for the status quo and high-rise locks cases appears in Table 7-1.

The capacity curves for the status quo and high-rise locks cases (1 through 7) appear as Figures 7-1 through 7-4. The summary outputs of average delay and transit times from the WAM resource files for cases 1 through 7, appear in Appendix I.

CAPACITY CURVES
STATUS QUO - 65,000 DWT

CASE 1 (WEFA 2020)
Q = 18,569 vessel transits; D = 0.9389 hours



CASE 1a (PCC 2010)
Q = 16,476 vessel transits; D = 0.8001 hours

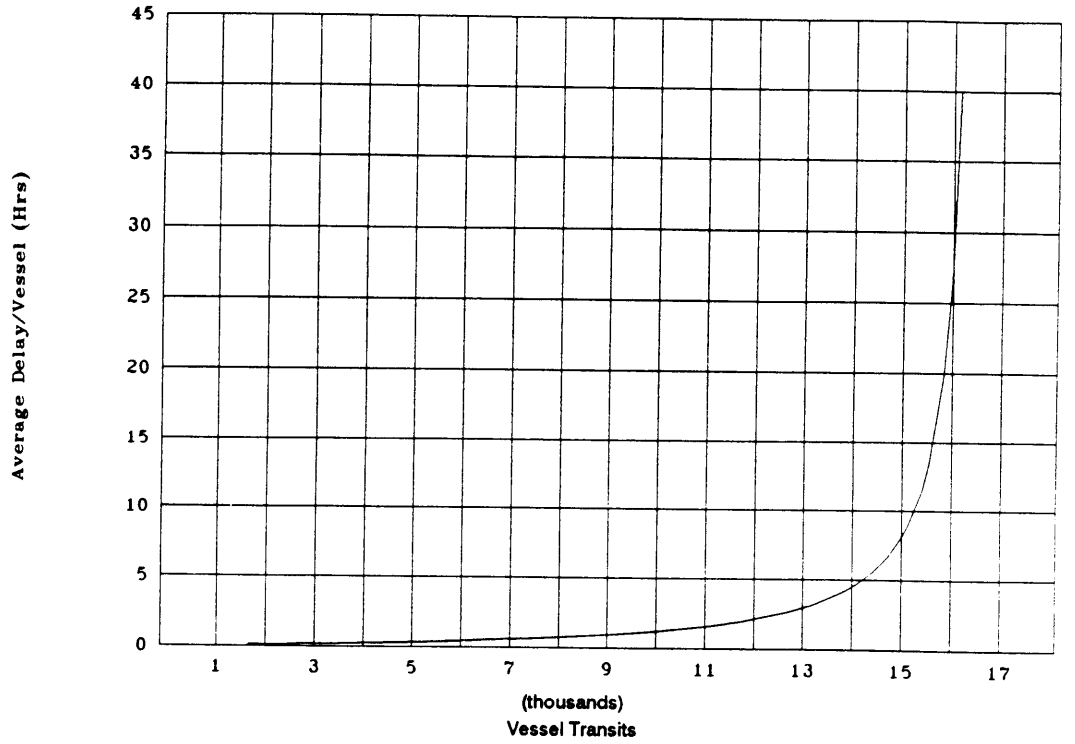
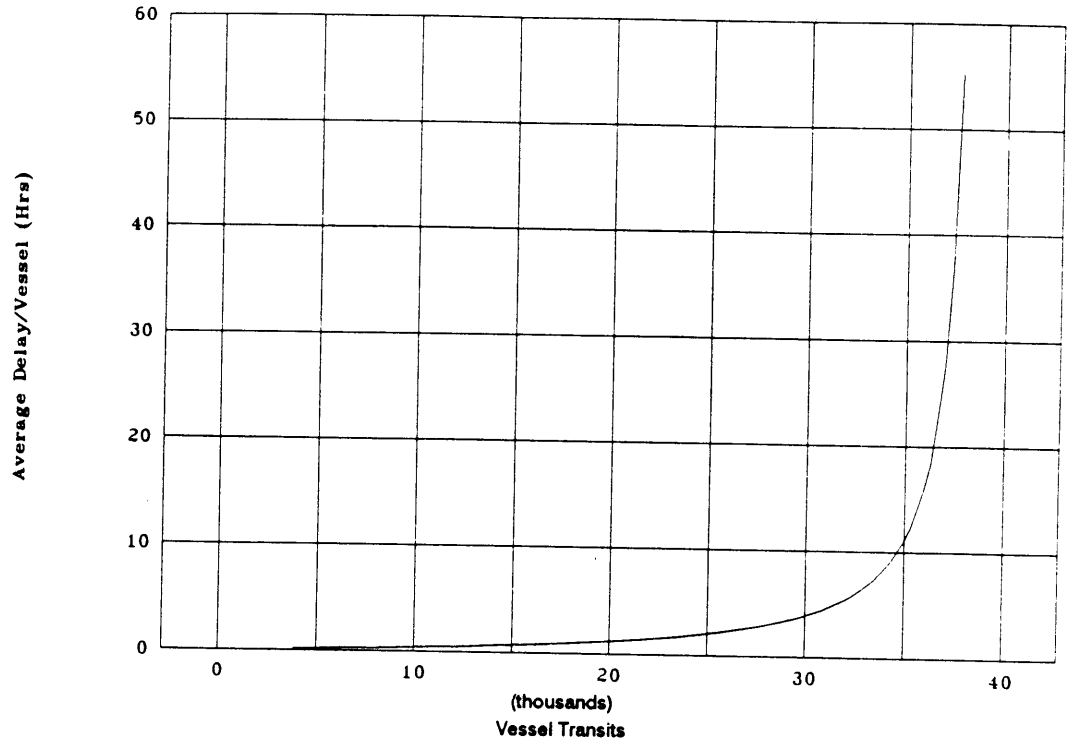


FIGURE 7-1

CAPACITY CURVES
HIGH-RISE LOCKS - 150,000 DWT

CASE 2 (1 Lock Lane)
Q = 38,463 vessel transits; D = 1.105 hours



CASE 3 (2 Lock Lanes)
Q = 56,741 vessel transits; D = 1.056 hours

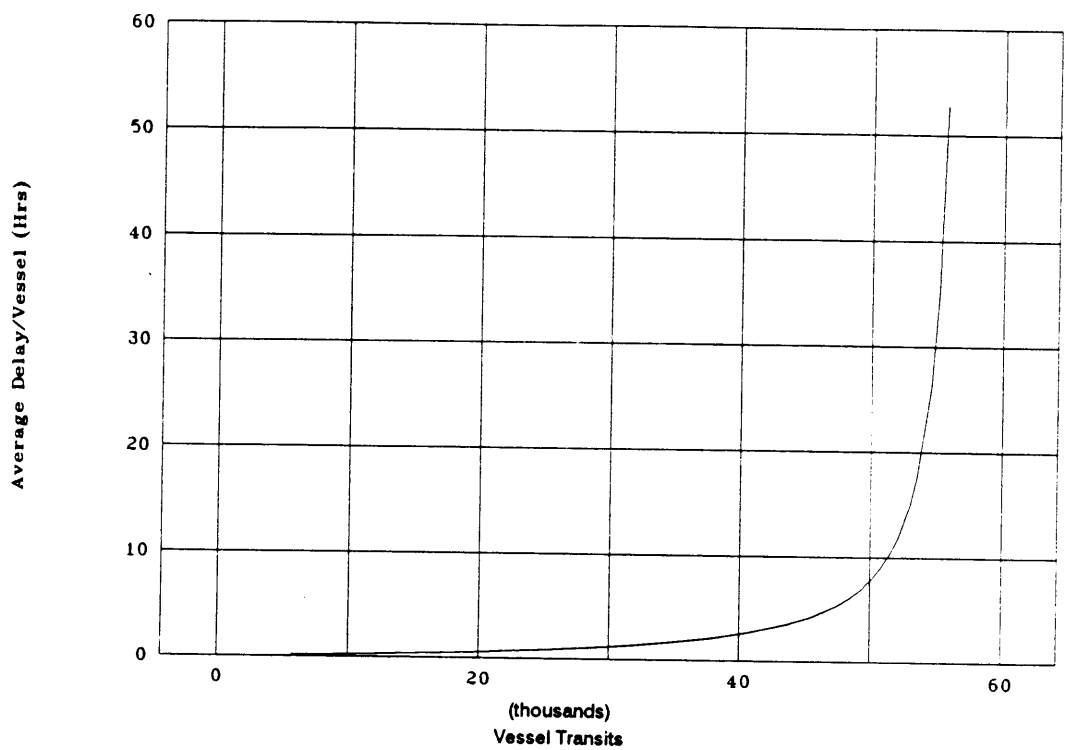
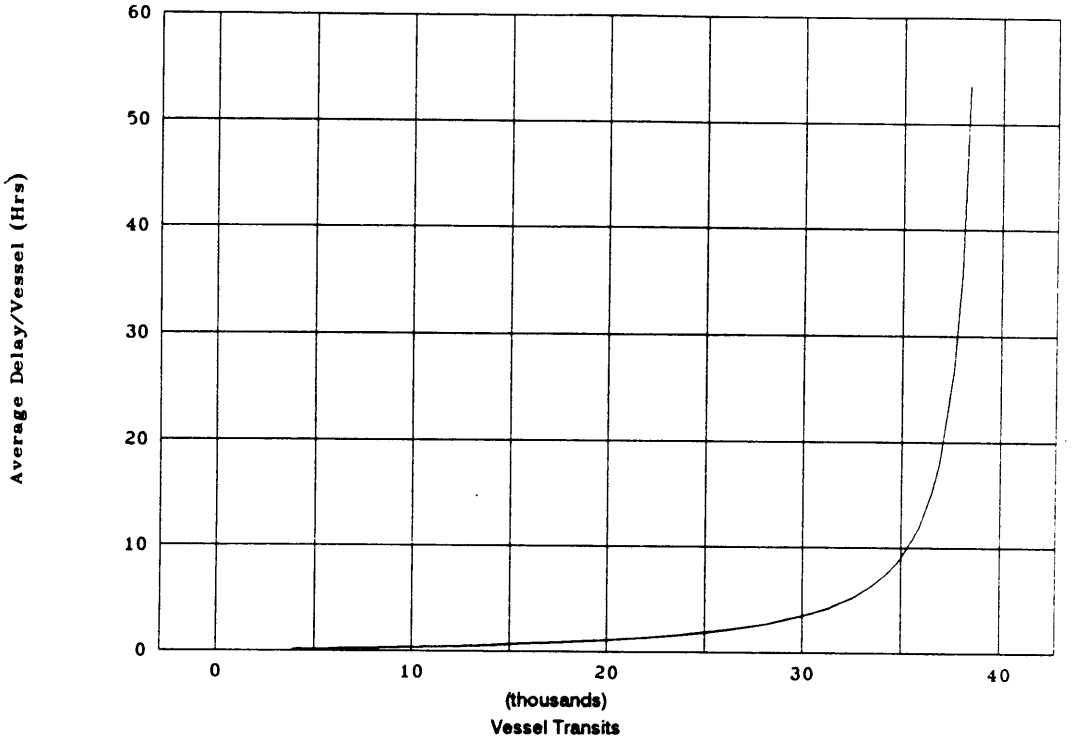


FIGURE 7-2

CAPACITY CURVES
HIGH-RISE LOCKS - 200,000 DWT

CASE 4 (1 Lock Lane)
Q = 39,136 vessel transits; D = 1.074 hours



CASE 5 (2 Lock Lanes)
Q = 59,846 vessel transits; D = 1.022 hours

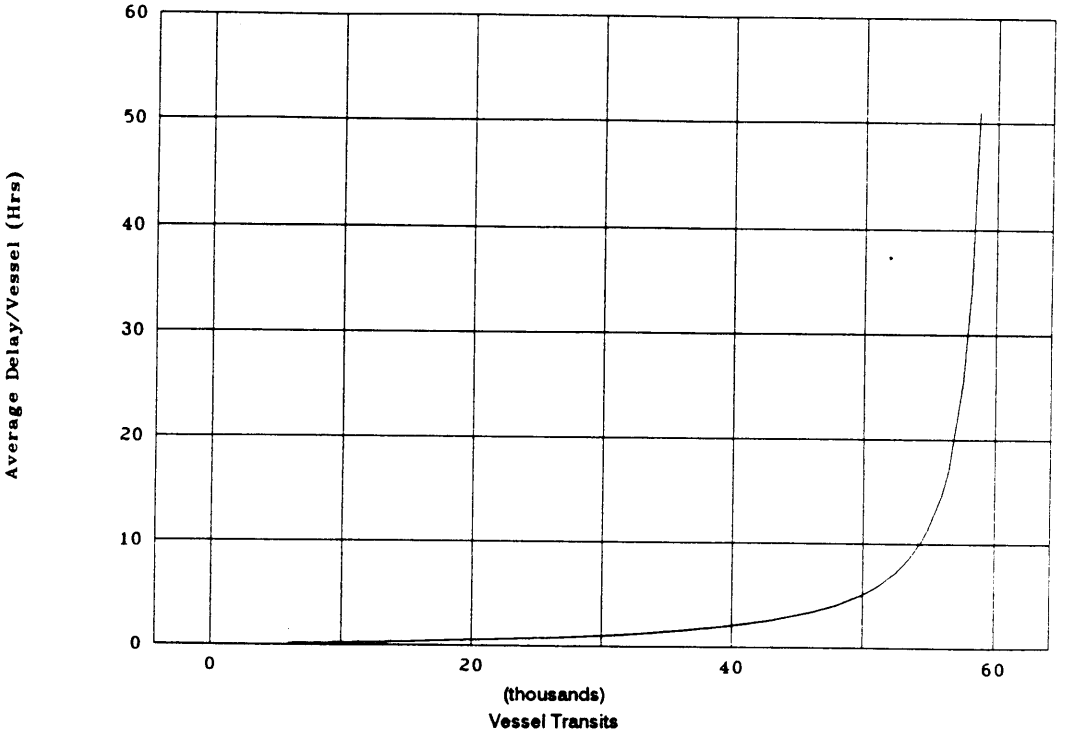
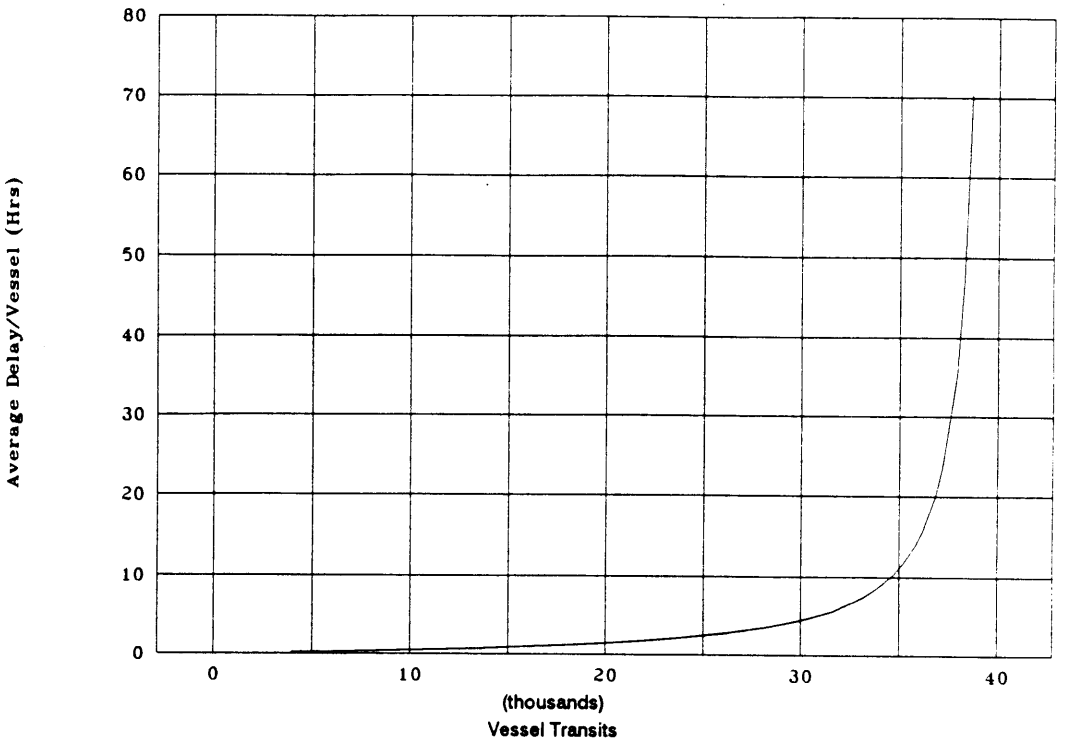


FIGURE 7-3

CAPACITY CURVES
HIGH-RISE LOCKS - ONE-LANE CULEBRA CUT

CASE 6 (150,000 DWT)
Q = 40,424 vessel transits; D = 1.764 hours



CASE 7 (200,000 DWT)
Q = 40,300 vessel transits; D = 1.652 hours

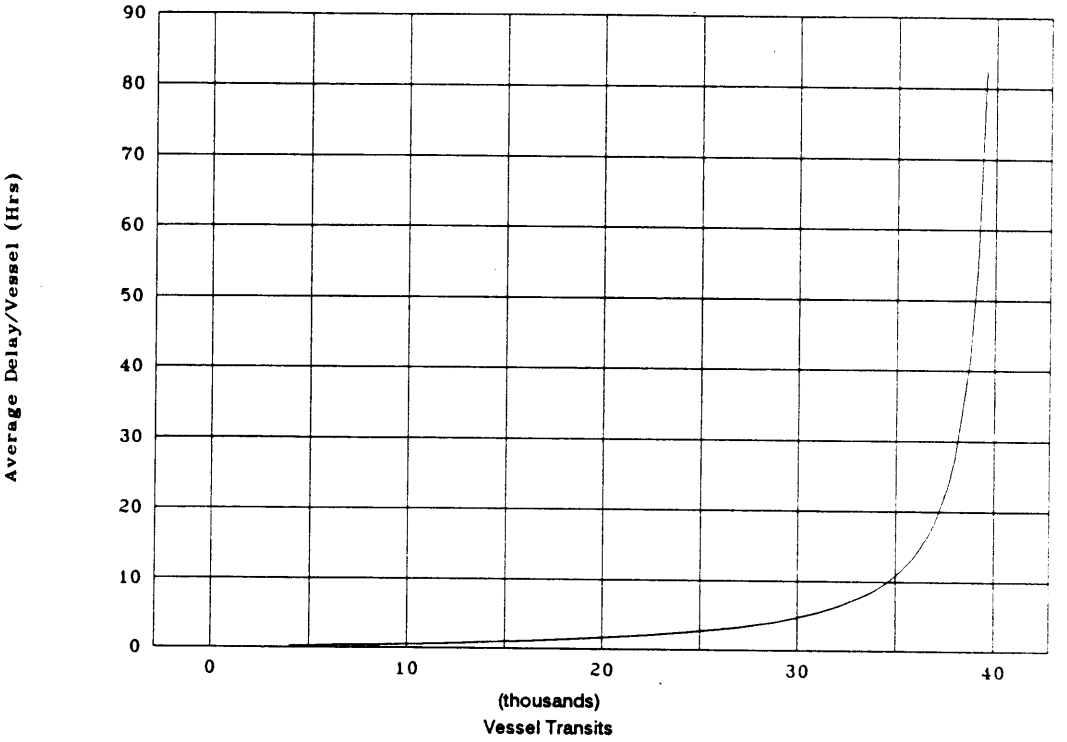


FIGURE 7-4

TABLE 7-1
SUMMARY OF SIMULATION RESULTS:
STATUS QUO AND HIGH-RISE LOCKS CASES

Case	Variable	Run 1	Run 2
1	Annual Transits	14,921	16,853
	Average Delay (hrs)	3.84	9.22
1a	Annual Transits	9.885	15,680
	Average Delay (hrs)	1.20	15.76
2	Annual Transits	23,626	34,060
	Average Delay (hrs)	1.76	8.55
3	Annual Transits	30,182	53,382
	Average Delay (hrs)	1.20	16.78
4	Annual Transits	24,662	36,238
	Average Delay (hrs)	1.83	13.43
5	Annual Transits	30,179	55,574
	Average Delay (hrs)	1.04	13.30
6	Annual Transits	23,622	34,528
	Average Delay (WAM)	2.10	9.89
	Ships' Scheduled Delay	0.38	0.44
	Total Average Delay (hrs)	2.48	10.33
7	Annual Transits	23,622	36,248
	Average Delay (WAM)	1.95	14.36
	Ships' Scheduled Delay	0.39	0.41
	Total Average Delay (hrs)	2.34	14.78

SEA-LEVEL CANAL ALTERNATIVES

The Sea-Level Canal alternatives are based on a cyclical operation, which requires three data points to produce a capacity curve. For the combined sea-level and status quo alternatives (8, 8a, 9, 9a, 9b and 10), because actual travel times differ along the two routes, it was more appropriate to use transit time (travel plus delay) as a measure, rather than delay time alone. This is also compatible with the dynamic route assignment logic in the model, which attempts to equalize transit time on the two routes.

In all cases, except the status quo, the 2060 ship mix was used in the model.

Alternative transit times of 15 hours and 19 hours were assumed as the basis of capacity for the combined sea-level/status quo cases. Since the travel (non-delay) portion of transit time through the status quo system is approximately 9 hours, these criteria are consistent with the delay criterion.

Because of the different operating procedures for the sea-level canal, as compared with the status quo system, it was not possible to develop composite delay or transit time curves for these systems. The principal reason is that the cyclic convoy operations of the single-lane sea-level channels impose a minimum average delay of several hours, even at very low traffic levels. Consequently, the following strategy was used to develop meaningful estimates of operational capacity for these cases:

1. The sea-level canal version of the WAM was used to simulate operation of the combined sea-level and status quo systems, including dynamic assignment of ships to the two channels. Runs were made at three traffic levels selected to span the knee of the capacity curve.

2. The simulation results for the sea-level portion of the system were used to develop a transit time vs. traffic level capacity curve for the sea-level canal only.

3. The capacity curve for case 1, the status quo system, was used to represent the operating characteristics of the status quo.

4. To estimate operational capacity at an average delay of 6 hours, the status quo traffic at 6 hours of delay was added to the sea-level traffic at a transit time of 15 hours.

5. To estimate operational capacity at an average delay of 10 hours, the status quo traffic at 10 hours of delay was added to the sea-level traffic at a transit time of 19 hours.

Steps 4 and 5 were accomplished using the delay and transit time functions from formulas 1a and 5a in Appendix H.

It was assumed that the ship mix of traffic in the status quo system in cases 8 through 10 will be approximately the same as the ship mix for case 1. This was verified by developing a representative delay curve for the status quo using the results from the case 8 simulations, and finding that this curve and the delay curve developed from the case 1 simulations were essentially the same.

Table 7-2 contains the inputs to computation of the transit time curves for the sea-level route of the sea-level canal alternatives. In each case, the results were obtained from various elements of the WAM output or the Foxpro post-processing program, as indicated in the table. The number of ships per year and the corresponding average total transit time were input directly into the equations for estimating the function parameters.

The actual capacity computation for the sea-level route for any transit time criterion was based on the formula:

$$q(t) = \frac{(t-T_o)\ Q}{(T-T_o) + (t-T_o)}$$

where;

$q(t)$ = traffic level (number of ship transits) at transit time (t);

and Q, T, T_o = canal capacity function parameters.

TABLE 7-2
SUMMARY OF SIMULATION RESULTS
SEA-LEVEL CANAL CASES

Case	Variable	Data Source[1]	Run 1	Run 2	Run 3
8	Ships/year	S	11,372	26,288	27,406
	Avg. Transit, hr.	S	8.90	14.13	29.90
9	Ships/year	S	2,622	21,424	29,100
	Avg. Transit Times, hr.				
	Single Lane Segment[2]	S	7.523	10.928	14.697
	Lock Delay	W/F	0.11	2.19	4.76
	Approach Channels[3]	W/F	3.768	3.768	3.768
	Total		11.40	16.89	23.22
10	Ships/year	S	2,564	21,358	29,098
	Avg. Transit Times, hr.				
	Single Lane Segment	S	7.620	10.490	13.050
	Lock Delay	W/F	0.06	1.05	1.61
	Approach Channels	W/F	3.581	3.581	3.581
	Total		11.26	15.12	18.24
9a	Ships/year	S	2,740	20,100	28,400
	Avg. Transit Times, hr.				
	Single Lane Segment	S	7.22	10.51	13.42
	Lock Delay	W/F	0.12	1.37	1.89
	Approach Channels	W/F	4.08	3.73	3.78
	Total		11.42	15.61	19.09
8a Half-Cycle	Ships/year	S	10,976	17,756	19,504
	Average Transit, hr.	S	9.14	13.53	39.77
9b	Ships/year	S	2,506	7.546	10.506
	Avg. Transit Times, hr.				
	Single Lane Segment	S	7.43	8.84	9.49
	Lock Delay	F	1.29	7.54	25.33
	Approach Channels	F	4.20	3.88	3.84
	Total		12.92	20.26	38.66

1 Key: S = WAM output file from sea-level canal module.
W = WAM print file.
F = Foxpro post processing of WAM resource usage file.

2 Sea-level channel between the tidal locks and the Atlantic end of the single-lane channel. Transit time includes delays due to convoy operations.

3 Transit time in channels outside of the single-lane segment, including lockage time but excluding lock delay, which is given in the preceding row.

The capacities for the sea-level route component thus computed are shown in Table 7-3. The capacity curves are shown in Figures 7-5 through 7-7.

TABLE 7-3
CAPACITIES OF SEA-LEVEL ROUTES*

Case	Number of Annual Vessel Transits	
	15-hr. Transit	19-hr. Transit
8	26,480	26,980
8a	18,190	18,790
9	17,270	24,750
9a	18,220	28,230
9b	4,690	7,060
10	20,980	30,500

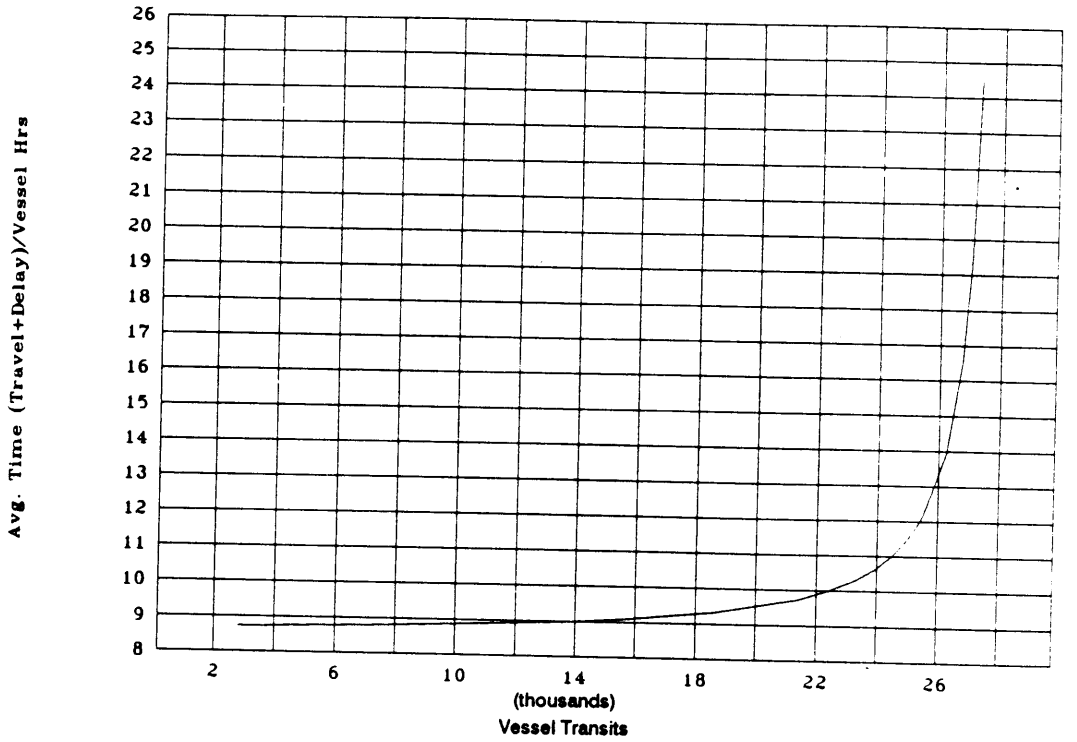
* When used in conjunction with the Status Quo Canal.

The capacities from Table 7-3 were then added to the capacity of the status quo route to arrive at the total capacity of the system. In all cases, the capacity of the status quo system was computed as 16,060 vessel transits for the 15-hr. transit time criterion and 19,980 vessel transits with the 19-hr. criterion.

It should be noted that the capacities shown in Table 7-3 are valid for the sea-level routes only when they are used together with the Status Quo Canal. The capacities of the sea-level routes as independent systems would be lower than those shown above, because ships of 65,000 dwt and under that just miss a convoy cycle would incur longer delays inasmuch as they would not have the option of using the alternative status quo route. For example, the capacity of the Case 8 sea-level route operated independently is estimated to be about 2,000 fewer ships than indicated in the table. At this level, the route would provide no reserve capacity for unanticipated delays and, of course, there would be no alternative to accommodate traffic when the route is down.

CAPACITY CURVES
ROUTE 10 - TIDE GATES (Sea-Level Only)

CASE 8 (2 Lane Atlantic Approach)
Q = 27,815; T_o = 8.681; T = 8.998



CASE 8a (1 Lane Atlantic Approach)
Q = 19,888; T_o = 8.378; T = 8.997

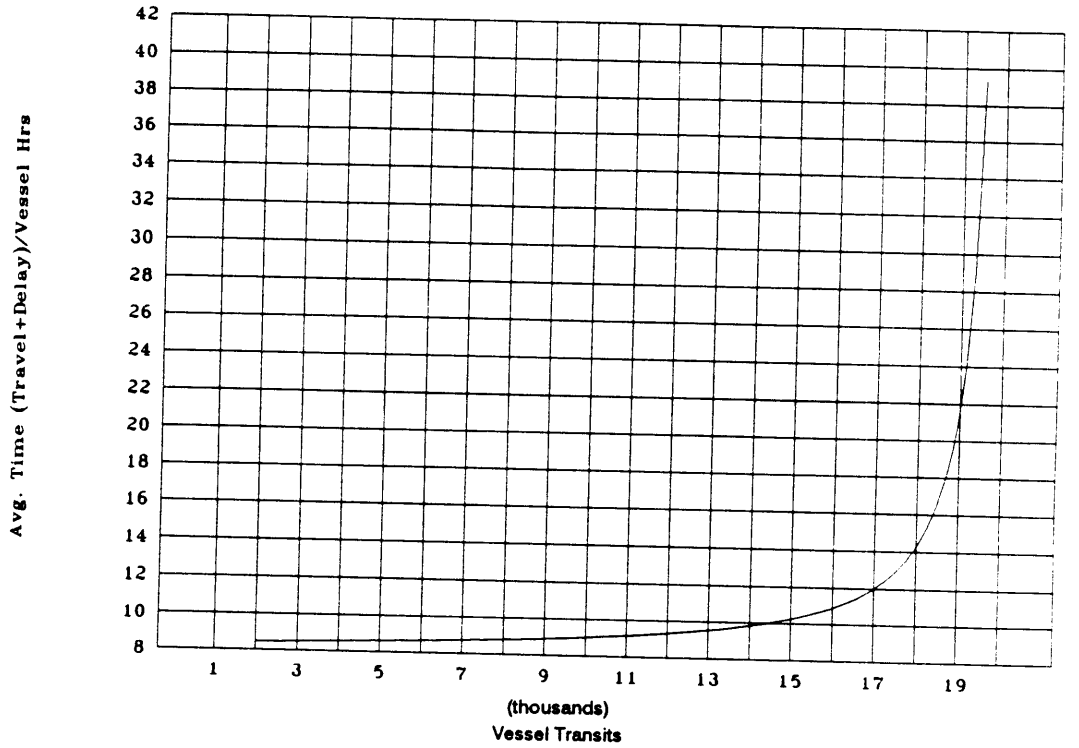
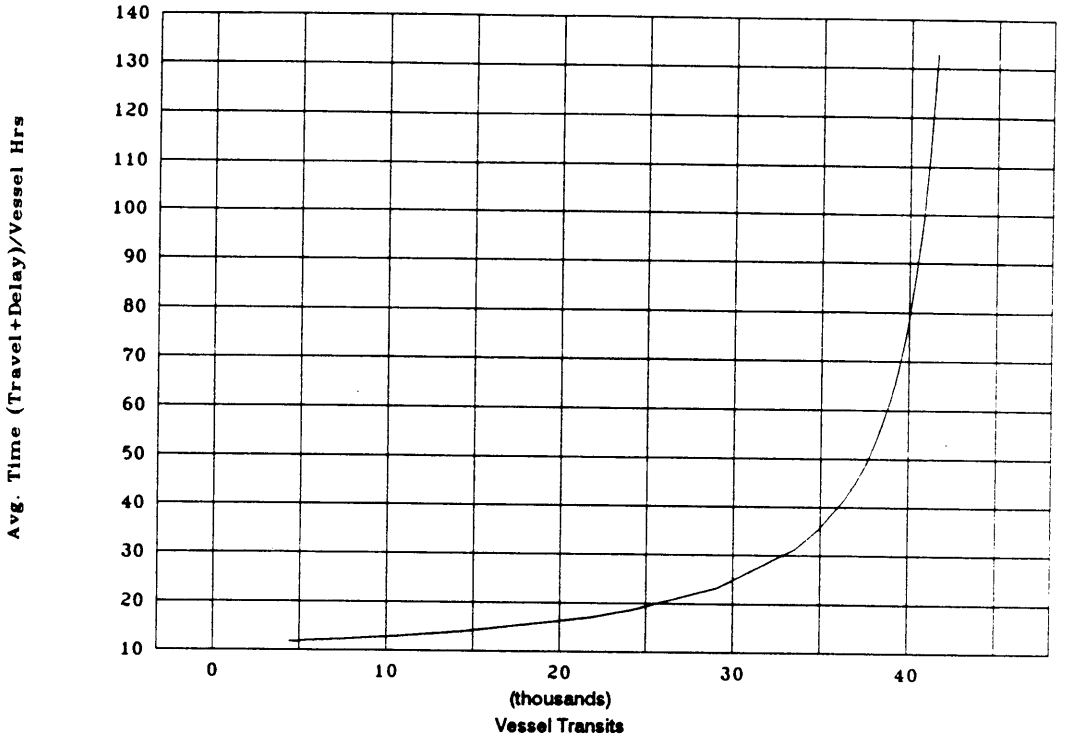


FIGURE 7-5

CAPACITY CURVES
ROUTE 10 - PACIFIC LOCKS (Sea-Level Only)

CASE 9 (3 Locks - Parallel)
Q = 43,615; T_o = 11.01; T = 17.10



CASE 9a (3 Locks - 2 Tandem, 1 Parallel)
Q = 63,210; T_o = 10.97; T = 20.92

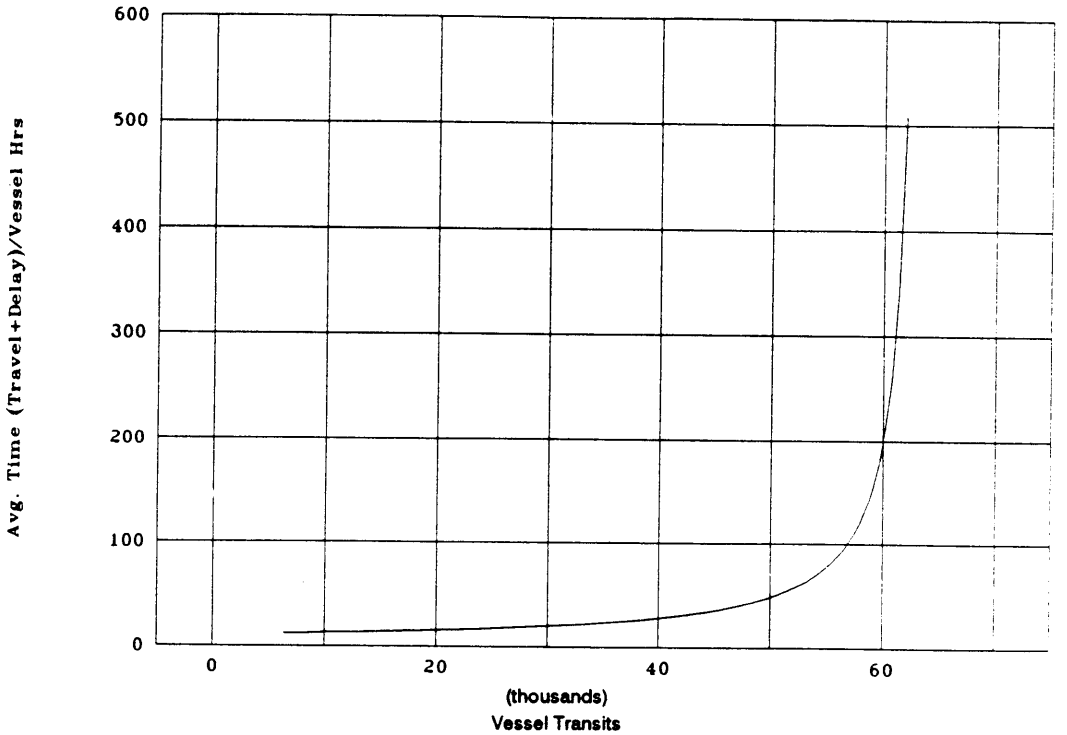
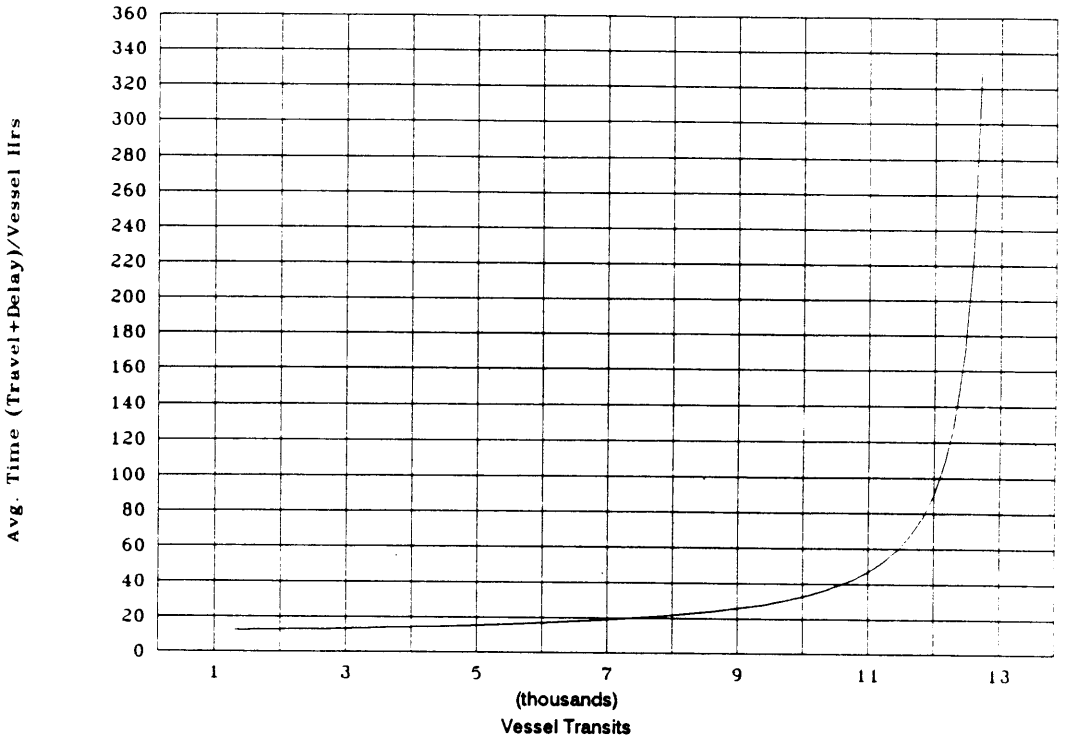


FIGURE 7-6

CAPACITY CURVES
ROUTE 10 - PACIFIC LOCKS (Sea-Level Only)

CASE 9b (1 Lock)
Q = 12,954; T_o = 11.40; T = 17.75



CASE 10 (4 Locks - Parallel)
Q = 56,661; T_o = 10.93; T = 17.85

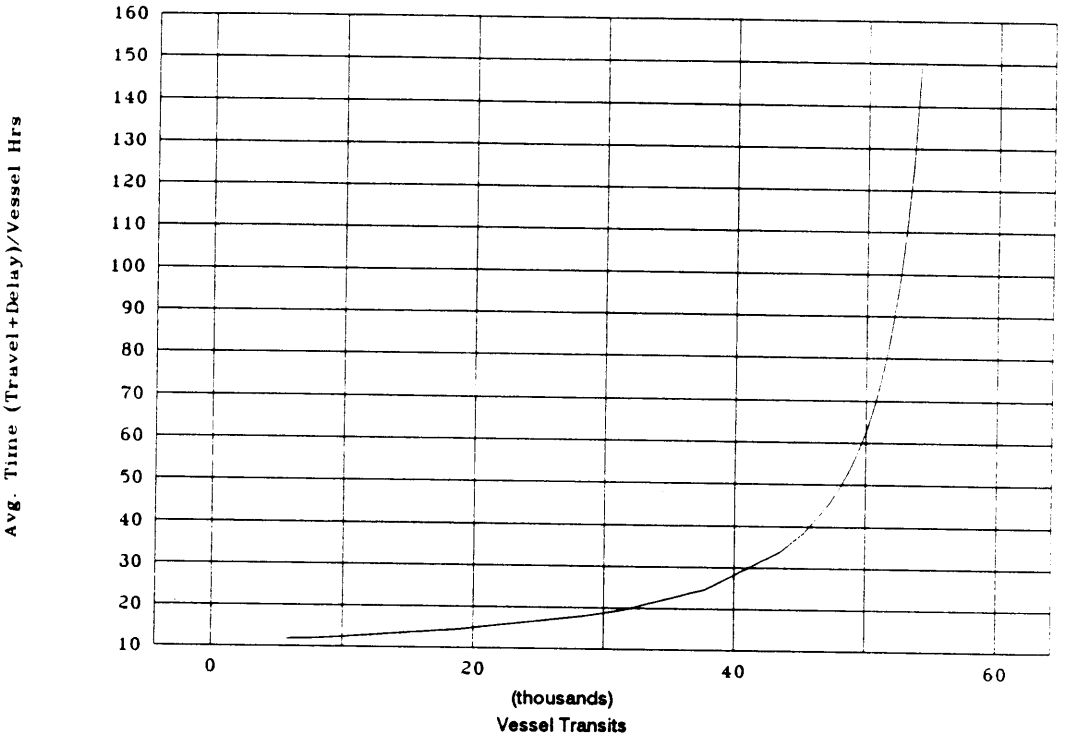


FIGURE 7-7

RESULTS AND CONCLUSIONS

The resultant capacities of the Phase 2 alternatives are presented in Table 7-4. Observations regarding the WAM outputs for each case appear in Appendix I.

Capacities computed in Phase 1 and the resultant Phase 1 conclusions appear in Appendix J.

The differences between Phase 2 and Phase 1 computed capacities (for the same alternatives) result from refinement of procedures and assumptions in Phase 2, including the following:

- refinement of the Waterway Analysis Model to reflect, among other things, dynamic assignment of ships to alternative routes, rather than judgmental; and demand generated relay lockages, rather than full-time relay lockages;

- larger clearances between ships and lock walls for the new locks, thus speeding lock entry and departure times;

- closer spacing between ships traveling in convoy in a sea-level canal.

By comparison of the capacities indicated in Table 7-4 with the vessel mix forecasts of Table 6-1, the following are concluded:

- The capacity of the Status Quo Canal will be exceeded by year 2020 under either delay criterion and either ship mix (WEFA or PCC).

- All of the High-Rise Canal alternatives (cases 2, 3, 4, 5, 6 and 7) have adequate capacity for vessel transit needs to year 2060, including those with a single lane of new locks and a single-lane Culebra Cut.

- For a single lane of new locks, there is no significant difference in capacity between maximum ship sizes of 150,000 and 200,000 DWT.

- The High-Rise Canal alternatives with two new lanes of locks (cases 3 and 5) have redundant capacity.

- The delays imposed by a single-lane Culebra Cut are small compared to the lock delays; therefore, cases 6 and 7 result in only a slightly lower capacity than the cases with a two-lane Cut and their capacities are still greater than forecasted traffic. The primary benefit of a widened Cut, therefore, would be safety rather than capacity.

- The combined sea-level/status quo cases 8, 8a, 9, 9a and 10, i.e., all of the cases studied except case 9b, single lock at the Pacific end,

have more than enough capacity for vessel transit needs through the year 2060.

- Case 8A, with a longer single-lane segment than Case 8 (55.5 Km vs. 40 Km) would have less capacity than Case 8, because, with a maximum convoy speed of 13 Km/hr., there would be insufficient time for a full convoy to transit the longer single-lane segment and allow the next convoy to enter during the 6¼ hour cycle of gate openings and closings. The result is that either cycles would have to be skipped, or, convoy lengths would have to be shortened. A longer cycle time (12½ hours) would produce higher capacity, but would require dredging deeper channels at the Pacific side. Nevertheless, the capacity of Case 8A is adequate to meet year 2060 forecasted needs.

- Based on the transit time criteria selected (15 and alternatively, 19 hours), case 9b -- the status quo plus a single-lane sea-level canal with a single lock at the Pacific -- would have insufficient capacity to meet the forecasted traffic levels. A similar system with two locks at the Pacific probably would satisfy the demand.

The Sea-Level Canal cases all produce results in which the status quo operates under highly congested conditions, to allow ships to avoid the long delays that are possible due to the fixed cycles of traffic through the single lane. For case 8, congestion delays are balanced between the two parts of the system. For cases 9 and 10, however, the 15 and 19 hour criteria for transit time reflect relatively uncongested conditions in the sea-level section, indicating redundant capacity which could be realized if a less restrictive travel time criterion were applied.

TABLE 7-4
ESTIMATED CAPACITY

Study Case	Conceptual Alternative	Maximum Ship Size 000s DWT	No. of New Lanes		Capacity-Annual Transits No. of Ships		Capacity M Tons	
			Channel	Lock Chambers	6 Hr. Delay*	10 Hr. Delay*	6 Hr. Delay	10 Hr. Delay
1	Status Quo	WEFA 65	-	-	16,100	17,000	374	395
1a	Status Quo	PCC 65	-	-	14,500	15,300	396	418
2	High-Rise Locks (85ft)	150	2	1	32,500	34,600	978	1,041
3	High-Rise Locks (85ft)	150	2	2	48,300	51,300	1,455	1,545
4	High-Rise Locks (85ft)	200	2	1	33,200	35,300	999	1,062
5	High-Rise Locks (85ft)	200	2	2	51,100	54,300	1,559	1,657
6	High-Rise Locks (85ft) Culebra Cut single-lane	150	2	1	31,200	34,400	941	1,038
7	High-Rise Locks (85ft) Culebra Cut single-lane	200	2	1	31,600	34,600	963	1,055
8	Route 10 Tide Gates & Status Quo	250	2/1	**	42,500	44,000	1,318	1,364
8a	Route 10 Tide Gates & Status Quo	250	1/1	**	34,300	35,800	1,063	1,110
9	Route 10, Pacific Locks & Status Quo	250	1	3	33,300	41,700	1,032	1,293
9a	Route 10, Pacific Locks & Status Quo	250	1	3***	34,300	45,200	1,063	1,401
9b	Route 10, Pacific Locks & Status Quo	250	1	1	20,800	24,000	645	744
10	Route 10, Pacific Locks & Status Quo	250	1	4	37,000	47,500	1,147	1,472

NOTE: See Figures 1-2 and 1-3 for schematics of alternative plans. Culebra Cut is two lanes, unless noted otherwise. Case 8a is the same as Case 8, except that a single-lane channel would be substituted for the 2-lane channel from the Atlantic end coastline to the north tide gate.

* The capacities of the sea-level canal cases (8 through 10) are based on transit times of 15 and, alternatively, 19 hours.

** Tide Gates

*** One double length chamber plus one standard chamber in parallel.

CHAPTER 8

SEDIMENT TRANSPORT

INTRODUCTION

One of the components that contributes to the maintenance costs of the Sea Level Canal Option is the cost of dredging. Sediment transport is the physical process that leads to the need for dredging in the canal. At the present time, there is little data available for estimating sedimentation. Hence, simple mathematical models were utilized to estimate sediment deposition in the canal and its approaches. The estimated quantities were then compared with field data gathered from the existing canal as a means of ascertaining the validity of the model predictions.

For modeling purposes, the study area was divided into two zones, namely, a canal zone and a coastal zone. The canal zone extends from the Pacific breakwater to the Atlantic breakwater. In this region ocean tides and river flows are predominant. The model LATIS was used to estimate flows and velocities in the canal zone. ROUTES, which makes use of the velocity field calculated by LATIS, was used to estimate sedimentation depths. The coastal zone is the shore line on either side of the breakwaters, at both oceans, where littoral drift is predominant. The program BEACHES was used to estimate the quantity of sediment transported by littoral currents and waves, or, effectively, to determine the changes along the coastline brought about by the construction of breakwaters.

The use of models LATIS and ROUTES for the canal zone and BEACHES for the coastal zone, to estimate sediment movement, is explained in the following pages. First, the study area and the different physical processes which influence sediment movement are discussed. Then, the idealization of the study area for modeling, the modeling approach including a brief description of the theory, and the results of the model prediction are presented. The model predicted sedimentation for the proposed canal is then compared with the field data for sedimentation from the existing canal. Finally, the summary and conclusions complete the chapter on sediment transport.

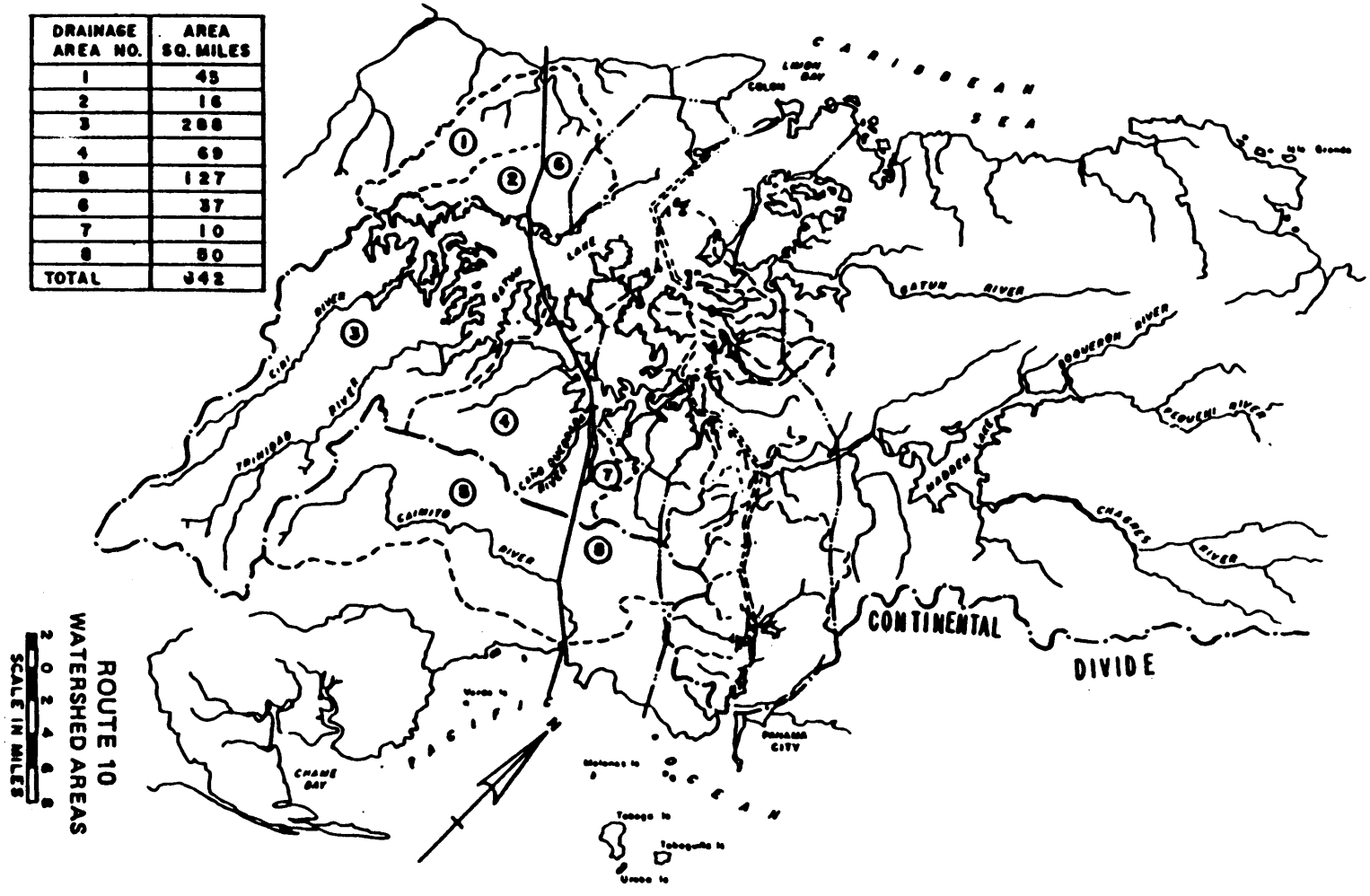
STUDY AREA

Physical Characteristics

The proposed sea level canal will be located southeast of the existing canal. The length of the canal from shore to shore is 60.8 km . It will pass through Gatun Lake and also intersect several streams and rivers. The total catchment area that would be draining into the canal is 1700 sq km (642 sq miles), out of which 470 sq km currently drain into the Pacific Ocean, while 1230 sq km currently drain into the Atlantic Ocean. The layout of the canal and the various drainage areas are identified in Figure 8-1.

PROPOSED SEA-LEVEL CANAL
LAYOUT OF CANAL

DRAINAGE AREA NO.	AREA SQ. MILES
1	45
2	16
3	288
4	69
5	127
6	37
7	10
8	50
TOTAL	642



ROUTE 10
WATERSHED AREAS

FIGURE 8-1

River Discharge and Sediment Movement

The interoceanic canal studies[1] identified fifteen major rivers that would intercept the canal. The rivers, their catchment areas, the invert levels and the side on which the streams will intercept the canal are tabulated in Table 8-1. These rivers or streams would be entering the canal at different invert levels at the point where they will intersect the canal (Figure 8-2). The streams will be a major source of sediment.

The movement of a sediment particle from the bed of a canal river is characterized by three processes, namely, erosion, transport, and deposition. For a particle to be eroded from the bed, the shear stress caused by the motion of water must exceed the critical shear stress for erosion. The critical shear stress for erosion is dependent on the type of bed material. It depends on whether the material is cohesive or not. Over the last 60 years researchers, engineers, and others working in the field of sediment transport have been trying to come up with a simple formula that is readily applicable to estimate bed erosion and transport. However, due to the complex nature of the problem of sediment transport, only limited success has been achieved.

The flows in the rivers bring in sediment according to the discharge, high flows bringing in large amounts of sediment and low flows bringing in minimal amounts of sediment. To explain this further, erosion occurs when the bed shear stress 'τ' exceeds the critical shear stress 'τ_c'. The equations representing sediment transport can be represented by:

$$g=K(\tau_b-\tau_c)^b$$

in which,

g	=	rate of sediment transport per time and unit width
K	=	constant
b	=	exponent
τ_c	=	shear stress at which sediments will move
τ_b	=	bed shear stress given by γRS_e
γ	=	unit weight of water
R	=	hydraulic radius
S_e	=	energy slope

and by the Darcy-Weisbach equation for normal flow:

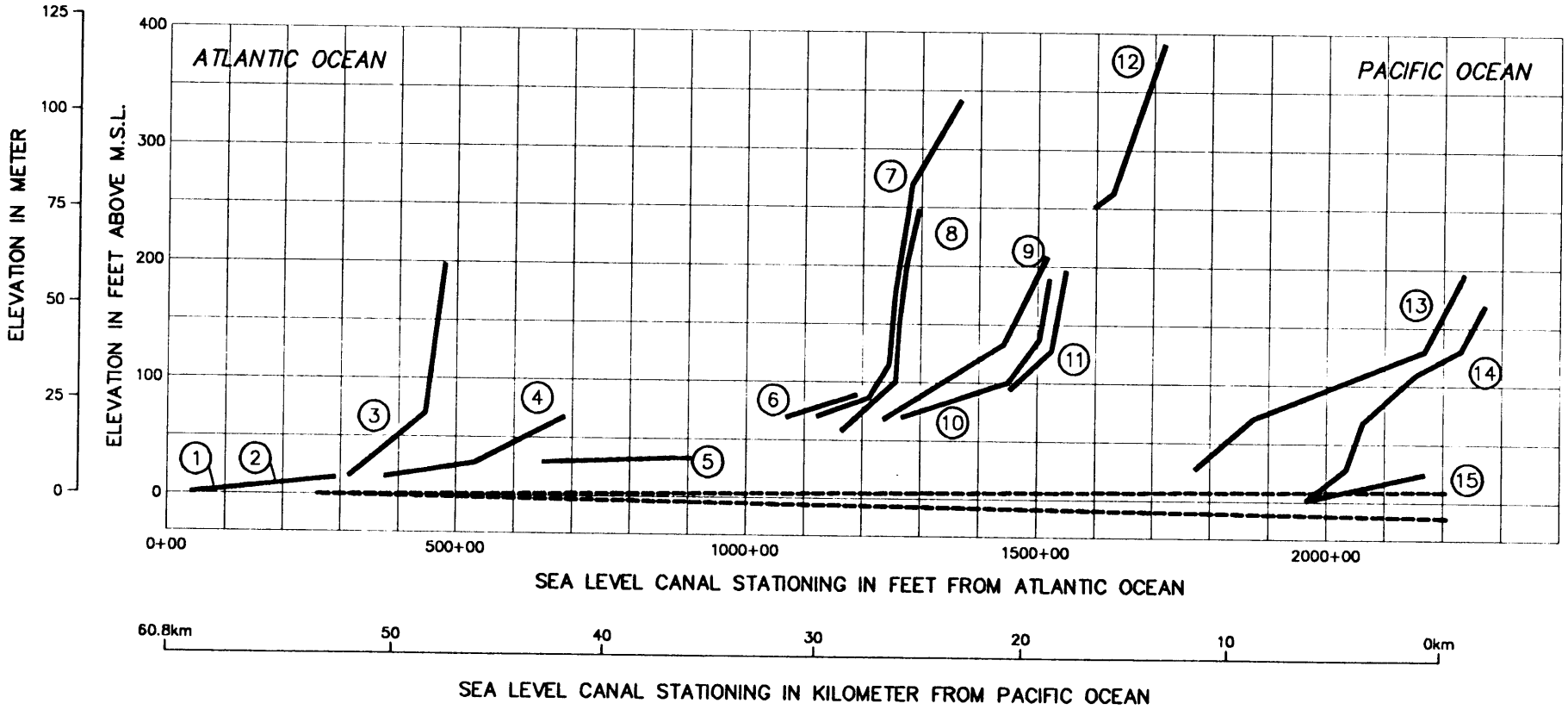
$$u=\sqrt{(8\frac{gRS_e}{f})}$$

In the above equation, 'g' refers to the gravitational acceleration and 'f' refers to the friction coefficient.

TABLE 8-1
RIVERS INTERCEPTING ROUTE 10 - DATA

No.	Name	Drainage Area (Sq.Miles)	Invert EL(MSL)	Bank	Dist.in Km From Atlantic
1	Lagarto	45.0	0.0	W	1.54
2	Arrieros	34.0	0.0	E	1.54
3	Quebrada La Escoba	3.5	15.0	E	9.26
4	Quebrada Brazito	16.0	15.0	W	13.88
5	Trinidad & Ciri	288.0	30.0	W	20.05
6	Los Azules	32.1	70.0	W	32.39
7	Quebrada De Chico	4.2	70.0	W	34.71
8	Mendoza	3.7	60.0	W	36.25
9	Cano Quebrada	28.6	70.0	W	38.56
10	Pescado	8.5	70.0	E	39.33
11	Santa Cruz	2.2	95.0	W	44.73
12	Congo	2.8	250.0	E	49.05
13	Caimito I	115.5	30.0	W	54.00
14	Martin Sanchez	11.4	0.0	W	60.16
15	Caimito II	47.0	0.0	E	60.93

PROPOSED SEA-LEVEL CANAL
PROFILES OF STREAMS INTERSECTED BY ROUTE 10



1. LAGARTO
2. ARRIEROS
3. QUEBRADA LA ESCOBA
4. QUEBRADA BRAZITO
5. TRINIDAD & CIRI
6. LOS AZULES
7. QUEBRADA DE CHICO
8. MENDOZA
9. CANO QUEBRADO
10. PESCADO
11. SANTA CRUZ
12. CONGO
13. CAIMITO I
14. MARTIN SANCHEZ
15. CAIMITO II

NOTE: Metric Values are approximate equivalents

SOURCE: Interoceanic Canal Studies (1970)

FIGURE 8-2

Assuming the hydraulic radius R≈h, depth of water, it can be shown that:

$$g = K(Q^{0.667} F(w, f, S_e, g) - \tau_c)^b$$

The above expression shows that the sediment discharge is dependent on the river discharge, 'Q' and the width of river 'w'. The rivers that intercept the canal have an annual cycle as represented by Figure 8-3, showing the flow in the Trinidad river, measured at El Chorro, for the years 1973 and 1974.[1] It illustrates the seasonality of generally high flows in October and November, low flows from January through May, and intermediate flows during the period June to September. Therefore, one could also expect an annual cycle in the amount of sediment discharged into the canal.

Ocean Tides and Sediment Transport

Another relevant hydraulic/hydrodynamic factor that influences the movement of sediment transport in the canal is the ocean tide at the breakwater entrances. The Pacific tides exhibit diurnal inequality and their fortnightly spring/neap cycle is not identical. A similar pattern could be expected for the velocity of flow which controls sediment movement. Compared to the Pacific tide, the Atlantic tide has an even more complex pattern.

The predicted tides for the month of January 1992 at Balboa and Cristobal, corresponding to the Pacific Ocean and the Atlantic Ocean, respectively, are shown in Figures 4-4 and 4-5.[2] Figure 8-4 is an idealized version of the variation of shear velocity with time, showing regions of deposition and erosion in a tidal situation. It shows that erosion takes place when the velocities are high and deposition takes place when the velocities are low, or zero. It also shows a region where there is neither erosion nor deposition. This is a region where both processes, erosion and deposition, are equal and there is neither net erosion, nor net deposition, but sediment transport would take place. Therefore, the movement of sediment due to tidal currents is also of concern.

Passage of Ships and Sediment Motion

When a ship travels in a canal having a limited width, the motion of the ship creates waves and turbulence. The effect of waves and turbulence on sediment motion is another aspect that has to be analyzed. Kuhn[3,4] identifies four factors caused by the movement of ships that cause erosion. They are, (a) ship generated waves, especially "breaking stern transverse waves," (b) return flows associated with bank suction, (c) sudden water level lowering along the vessel, and (d) propeller jet or propeller wash.

Very often the waves that are of major concern are the stern transverse waves. These waves cause high orbital velocities and erosion on the banks, thus contributing to the sediment budget. The erosion is limited to a region above and below

TRINIDAD RIVER AT EL CHORRO
Monthly Mean Flows - 1973 & 1974

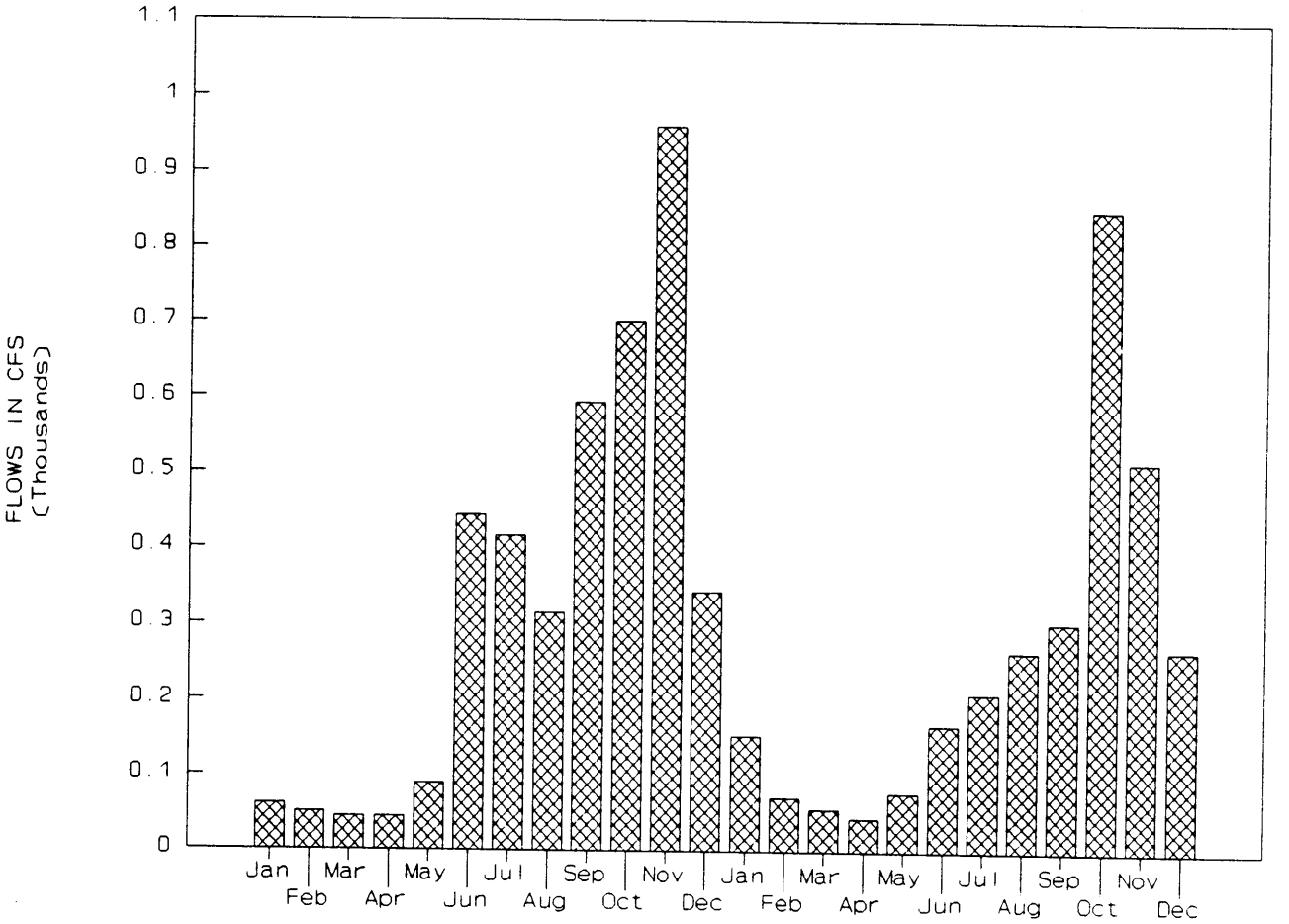
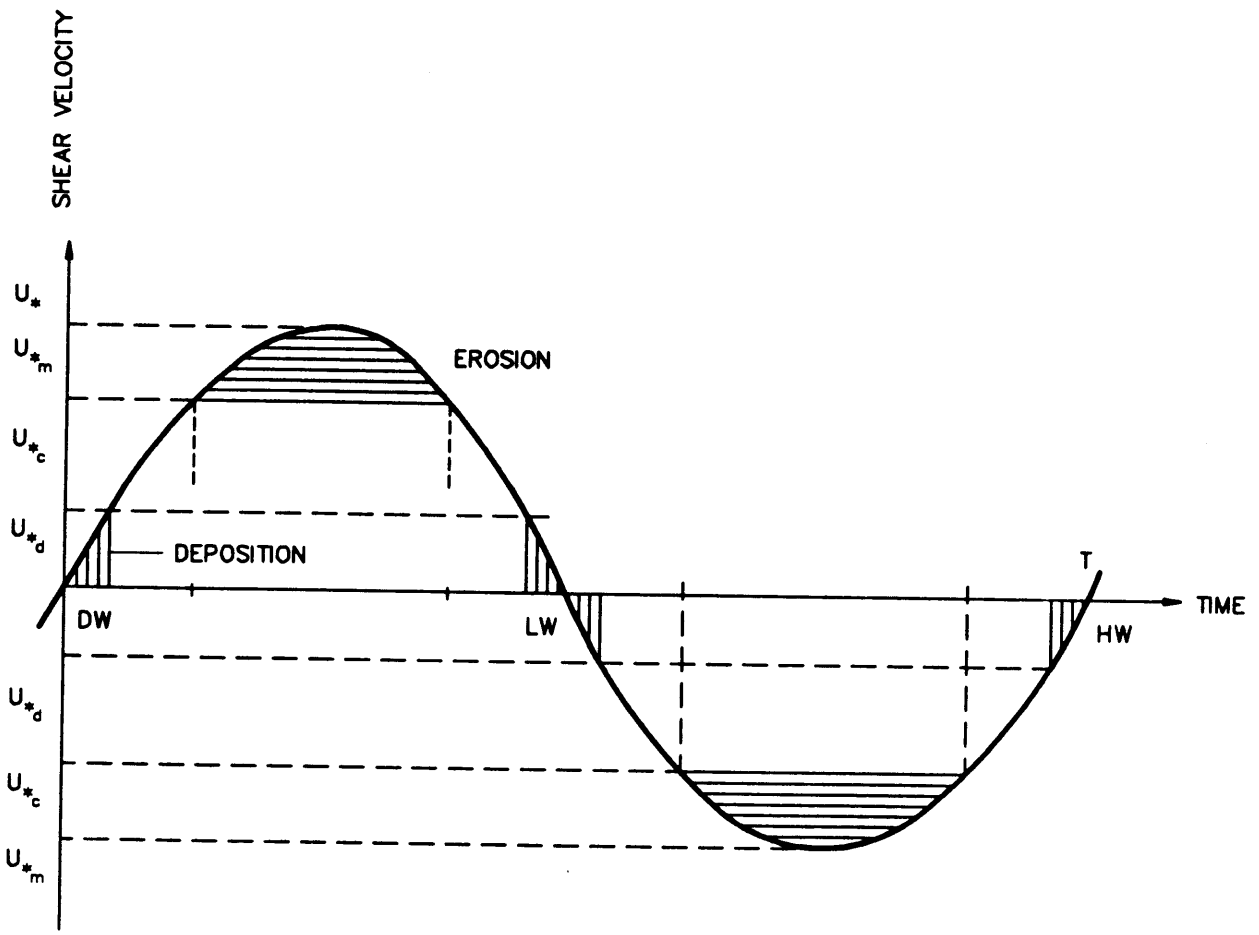


FIGURE 8-3

PROPOSED SEA-LEVEL CANAL
EROSION AND DEPOSITION TIDAL CYCLE



U_{*m} = Maximum Shear Velocity

U_{*c} = Critical Shear Velocity

U_{*d} = Shear Velocity for Deposition

FIGURE 8-4

the water surface. According to Burt,[5] a wave steepness of 0.01 changes the critical angle of 20° in still water to a critical angle of 9°. In addition, the wave action causes the hydrostatic pressure to vary very rapidly, affecting the stability of the banks.

Return flows with very high velocities create a larger shear stress along the side of the canal. The higher shear stress is far above the critical shear stress to cause erosion and the banks are eroded.

Another aspect observed in the model studies is the drawdown of the water level along the length of the ship. It has been observed that while small vessels cause negligible drawdown, big vessels cause a large drawdown.[6] A sudden lowering of the water level increases the groundwater pressure underneath the side slopes of the banks and affects the stability of the slopes. Collapse of side slopes, into the canal, contributes sediment.

Finally, the jet flow due to propellers erodes the bottom of the canal and bottom of the slopes. This is common at canal bends and places from where a ship starts.[3,6,7]

Ship Generated Waves

Progress has been achieved recently in the area of ship-generated wave analysis for fuel-efficiency. These results are presented, for example, in Transactions, Society of Naval Architects and Marine Engineers, Journals of Society of Naval Architects, and Journals of Ship Research. Most of recent ship-generated-wave analyses have been made in the area of CFD (e.g., Computational Fluid Dynamics), frequently using supercomputers.

For waterway design purpose, relatively few data are available on ship-generated waves in a restructed channel (e.g., Proceedings, PIANC).

Wave height generated by a ship is a function of Froude number which is:

$$F_n = U / \sqrt{gL}$$

in which, U = ship speed,
g = gravity, and
L = ship length;

or

$$F_h = U / \sqrt{gh} \text{ in shallow water}$$

in which, h = water depth.

It is known that when F_h is increased and approaches the critical case where $F_h = 1$, a ship-generated wave is significantly pronounced. For example, the value of

critical speed in 12m (40-ft) deep water is 21 knots. However, due to the speed limit within a canal, F_h is much lower than that situation.

In a canal, the generated wave is strongly influenced by:

(a) blockage factor (ship size relative to canal size); and
(b) ship speed.

Blockage factor B_f can be presented by sectional area ratio as follows:

$$B_f = A_c / A_m$$

in which, A_c = canal sectional area
A_m = midship sectional area

Due to this blockage A_c / A_m, a ship proceeding in a canal generates pressure differences in the vicinity of the ship. It can be treated by the Venturi-meter principle using a continuity and Bernoulli equation.

$$\Delta p = \rho/2\ U^2\ (1 - A_c / A_m)^2$$

This pressure difference generates, for example, water elevation H_w in front of the bow.

$$\Delta p = \rho g H_w$$

Such an approach has been made to estimate ship-generated waves as shown in previous Proceedings, PIANC.

Since the actual ship-canal system includes a substantial magnitude of viscous losses, an empirical approach should be made, fully reflecting actual data obtained in the ship-canal system. Through such a procedure, sufficient accuracy can be achieved in ship-generated-wave predictions in a channel.

An effort has been made at this time to estimate the general magnitude of ship-generated waves for a range of ship sizes and speeds for the sea-level canal case. Results obtained on the basis of continuity and Bernoulli equations with the inclusion of empirical factors are shown in Table 8-2.

The canal will be excavated through different types of soils which will influence the rate of erosion. To prevent erosion due to ship-generated waves or the other factors discussed in the previous paragraphs, protection along the side slopes of the canal is often provided. Contribution of sediment due to any of the above factors and the type of side slope protection are matters to be considered during detailed design.

TABLE 8-2
WAVE GENERATED IN CANAL

Ship Type	Beam B (m)	Draft d (m)	Width of Canal Wc (m)	Depth of Water Dw (m)	Speed V (kt)	Wave Height Hw (m)	Hw/d
250K	60.04	19.51	190	24.50	7.50	0.91	0.05
200K	49.98	18.59	190	24.50	7.50	0.83	0.04
150K	43.28	16.76	190	24.50	7.50	0.73	0.04
65K	32.31	13.72	190	24.50	7.50	0.57	0.04
250K	60.04	19.51	400	24.50	7.50	0.61	0.03
200K	49.98	18.59	400	24.50	7.50	0.54	0.03
150K	43.28	16.76	400	24.50	7.50	0.47	0.03
65K	32.31	13.72	400	24.50	7.50	0.36	0.03
250K	60.04	19.51	400	23.75	6.50	0.46	0.02
200K	49.98	18.59	400	23.75	6.50	0.41	0.02
150K	43.28	16.76	400	23.75	6.50	0.37	0.02
65K	32.31	13.72	400	23.75	6.50	0.28	0.02

Breakwaters and Littoral Drift

Breakwaters have been proposed at both ends of the canal to prevent siltation of the canal and to protect ships from strong winds. Both wave action and tidal currents influence sediment movement at the entrances. Furthermore, the breakwaters alter the entire pattern of littoral transport along the coastline.

Landslides, Land Use, Tide Gates, and Gate Operation

Landslides along the canal are another source of sediment. Any changes in the existing land use practices may also increase sedimentation. One such practice is the slash-and-burn agricultural technique used by the farmers. This has eliminated the forests along the existing canal causing increased erosion in the watershed and siltation in the existing canal. Such a situation may arise in the future along the proposed canal.

In addition to the above, such other factors as the method of operating the canal, and construction methods, would also alter the pattern of sediment transport. For the ships to navigate, safely, two options have been proposed; (a) the tide gate option and (b) the lock option. The operation of either gates or locks would control the movement of sediment in the canal.

In order to have an unhindered construction schedule, it has been proposed that diversion canals and dams be constructed to prevent the flows from the various rivers from entering the canal. This would ease construction and also eliminate any sediment input into the canal from the streams. However, the cost of constructing the dams, diversion canals and other features is high. Therefore, the cost and the technical aspects of this proposal have to be properly assessed before the proposal may be adopted in the scheme.

Summary

The sediment movement in the canal is influenced by several factors. River discharge, ocean tides, interaction of currents and waves, ship generated waves, construction of breakwaters, operation of the tide gates, and land use are some important causes that have to be considered in estimating the amount of sediment transported in a year. However, the above processes, illustrated in Figure 8-5, can be broken into several parts, as follows: (a) the canal zone between the coasts where the tides and the river flows interact, (b) the coastal zone where the waves are predominant, and (c) the entrances to the breakwaters where the combined effect of currents and waves are felt. The operation of the tide gates and locks has also been taken into account in a schematic matter.

MATHEMATICAL MODELING

General

As mentioned in the introduction, the study area was divided into two zones for mathematical modeling, the canal zone and the coastal zone. The hydrodynamics and sedimentation in the canal zone were investigated with the aid of programs LATIS and ROUTES respectively. The program BEACHES was used to study littoral drift in the coastal zone. A description of the models and the details of modeling, namely, representation of the study area by nodes and links, and selected results, are presented in this section.

DESCRIPTION OF MODELS

Model ROUTES

The model LATIS, a quasi-two dimensional model which represents a water body as nodes and links, creates the necessary input data for the model ROUTES. As LATIS was used in Phase I to estimate water velocities in the canal for different configurations, the use of ROUTES provides a continuity in the methodology. The fluxes of each sediment class interval into or out of a node are computed by ROUTES and is balanced with changes in sediment concentration at the nodes and depths of sedimentation. It does not explicitly take into account diffusion-dispersion which is considered negligible as compared to advection. A parameter 'α' which

PROPOSED SEA-LEVEL CANAL
SEDIMENT TRANSPORT

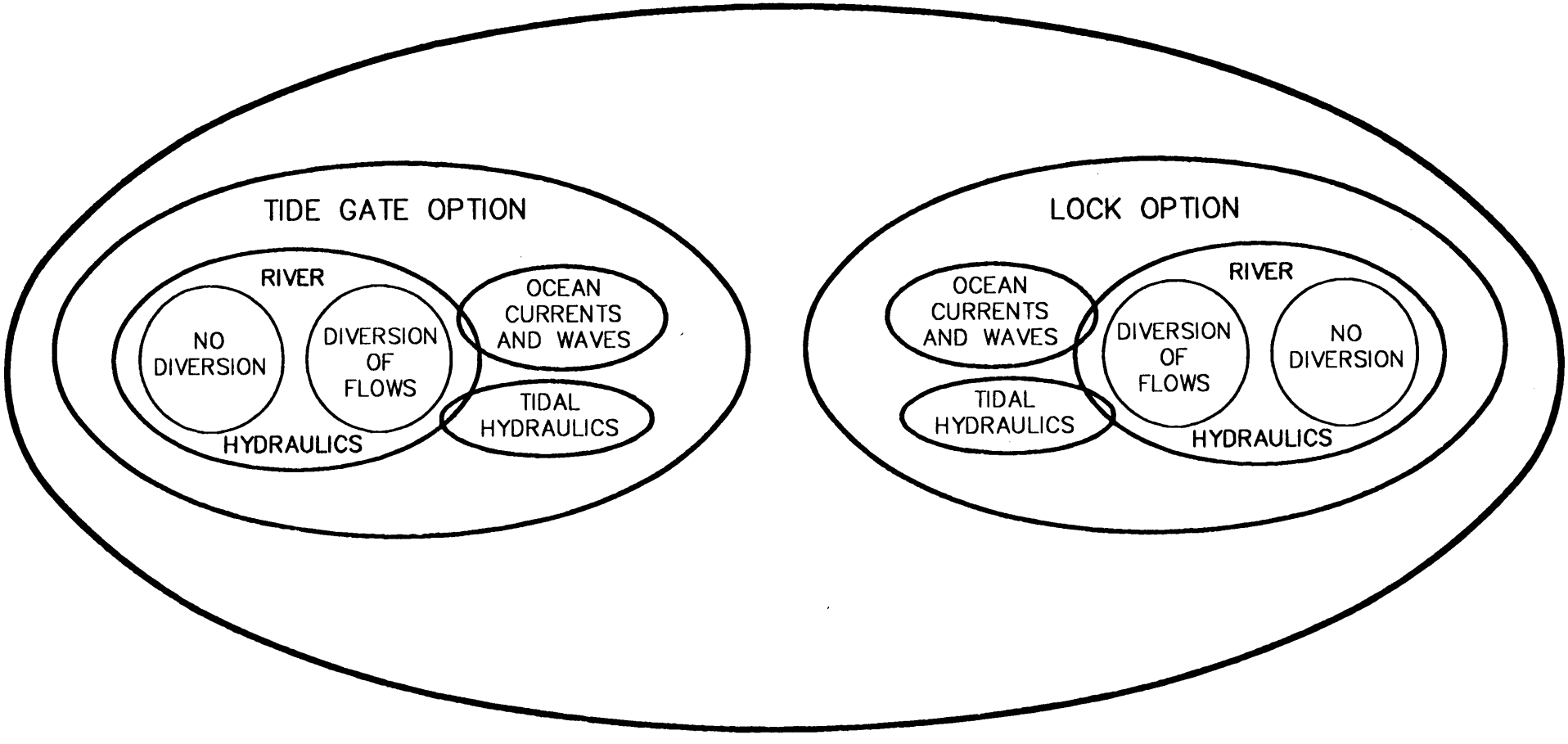


FIGURE 8-5

weights the concentrations of adjacent nodes is used to take into account dispersion. It is also an effective adjustment parameter.

The sediment routing model assumes a uniform concentration for the entire water column. It is also assumed that the suspended sediments travel at the same velocity as water. An explicit finite difference solution is obtained for the mass conservation of each fraction diameter of sediment in suspension in a node during a computation time interval. The computation balances the flux of sediment entering or leaving the node with the increase or decrease of sediment mass in suspension in the node and the bottom deposits during the same time interval. The mass in each node is converted to volume using a common deposit dry density.

The following finite difference expression of the sediment mass balance is written with the assumption of a deposit dry density of 1.0. A correction may be introduced in the final deposit depth if the deposit dry density is different.

$$V_i^{n+1} C_i^{n+1} - V_i^n C_i^n - \sum_{j=1}^{m} C_{ij}^n Q_{ij}^n \Delta t + V_i^n C_i^n \frac{W_d \Delta t}{Y_i^n} = O$$

in which,

- V_i = water volume in node i;
- C_i = conc. in node i (dry weight of suspended material per unit volume);
- C_{ij} = concentration in flux between nodes i and j;
- Q_{ij} = water discharge between i and j;
- Δt = time interval;
- W_d = settling velocity of particle fraction with diameter d;
- Y_i = water depth in node i;
- m = number of nodes connected to node i; and
- n = time increment superscript.

The flux concentration is weighted as follows:

$$C_{ij}^n = \alpha c_i^n + (1-\alpha)\, c_j^n \quad 0 \le \alpha \le 1$$

The weighting coefficient α is selected so that the node supplying the flow has a higher weight.

The fluxes through the links connecting node 'i' to the adjacent nodes are compared to those that would result from the application of Toffaletti's[8] expression for sediment transport. If the fluxes computed with the existing concentrations are higher than the fluxes computed with the concentrations obtained from Toffaletti's formula, the concentrations obtained from Toffaletti's formula is not used. Howev-

er, if the calculated concentration is lower than that obtained by Toffaletti's formula, the value obtained with the aid of the formula is used and the material is assumed to be picked up from the bed. In effect the bed is eroded. However, the program does not allow the bed to be scoured below that of the existing bed elevation. The flow chart in Figure 8-6 illustrates the method of estimating sediment deposition using ROUTES. A description of the model is included in Appendix K.

Model BEACHES

A brief description of the theory, the model algorithm, and the input data requirements are given below. For a more detailed version the reader is referred to Reference 10. The basic approach is studying sand flux and its relationship to sand storage. An expression widely used and documented in the Shore Protection Manual[9] is used to estimate sand flux.

$$Q = 7.5 \times 10^3 P_l$$

in which,

Q = longshore transport rate of sediment in cubic yards per year; and

P_l = linear theory longshore component of wave energy flux in ft-lb/sec/ft of shoreline, given by:

$$P_l = \frac{\rho g^2}{64\pi} H_o^2 \, TK_R^2 \sin 2\,\alpha_b$$

in which,

ρ = mass density in lb-sec^2/ft^4;

g = gravitational acceleration in ft/sec^2;

Ho = deep-water height in feet;

T = wave period in seconds;

K_R = refraction coefficient defined as $(\cos \alpha_c / \cos \alpha_b)^{1/2}$;

α_c = angle between deep-water wave crest and shoreline in degrees; and

α_b = angle between breaking wave crest and shoreline in degrees.

The main steps in the beach evolution model are as follows:

(a) For a given drift direction, fluxes are computed with the aid of beach configuration, wave climate, and different incident angles. The fluxes within the diffraction zone are corrected for diffraction and breaker angle variation. Different distributions for fluxes are obtained from different incident angles. The average of all the flux distributions is used to compute the beach excursion corresponding to the particular drift direction.

(b) The same procedure is repeated for the other direction, starting again from the same initial conditions and fluxes for the new drift direction.

FLOW DIAGRAM OF MODEL ROUTES - I

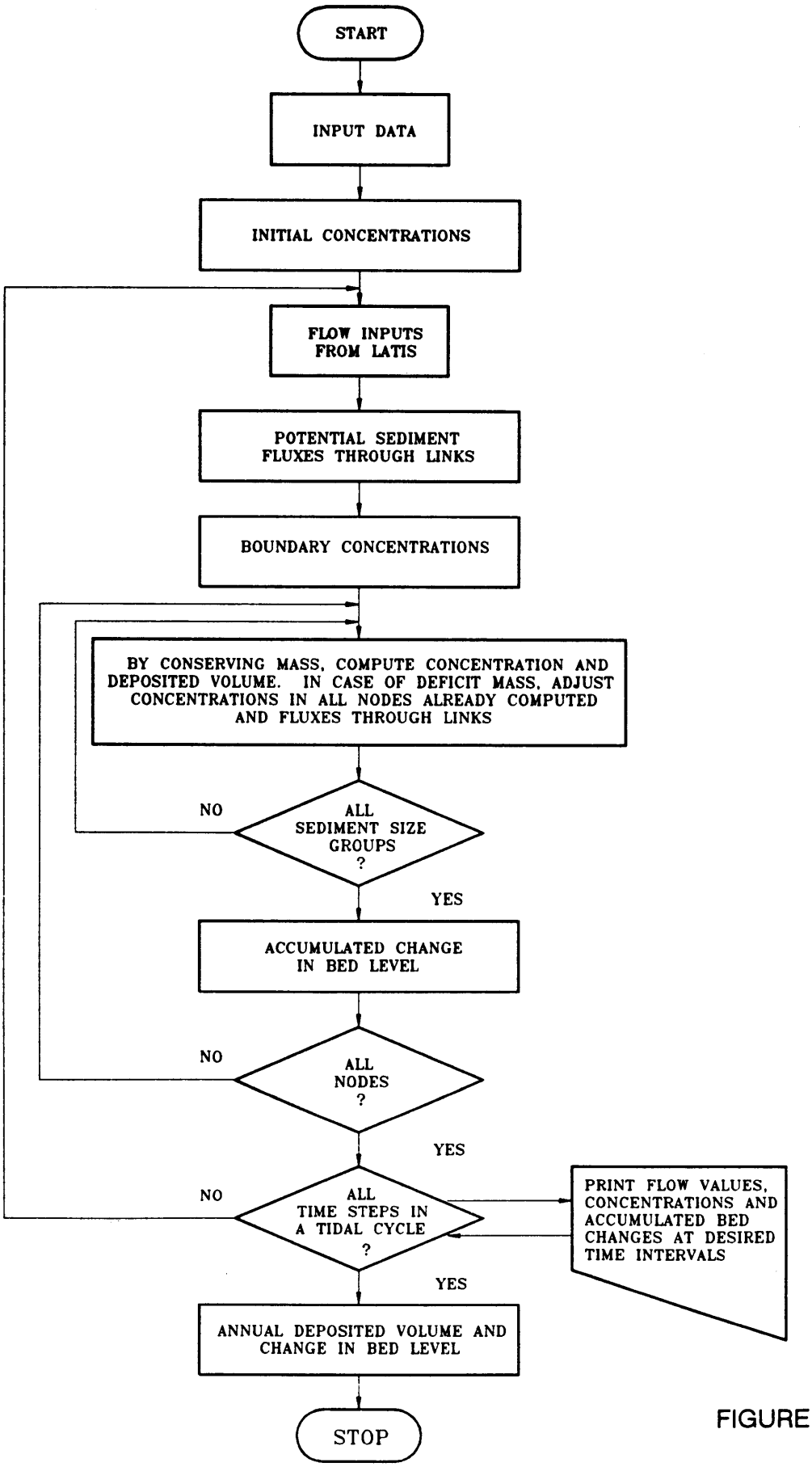


FIGURE 8-6

(c) The resultant beach excursion for the current time is obtained by superimposing the results of both analysis.

In order to run the model effectively, the following data are required:

(i) Length of structure,
(ii) Initial beach configuration,
(iii) Active beach depth,
(iv) Representative time series of wave height, period, and direction.

The length of structure is obtained from the designer. Bathymetric data and measurements along the beach would provide the initial beach configuration. Active beach depth is neither easy to measure, nor easy to estimate. However, some approximations or expressions can be used to estimate the parameter. The model requires the use of wave heights, periods, and directions obtained through statistical concepts. In the absence of wave data, hindcasting procedures such as the SMB procedure described in the Shore Protection Manual (1984) can be used to obtain the necessary information. Hindcast waves have to be corrected for refraction, dispersion in shallow water, and wind duration limitation.

Modeling the Canal Zone

Tide Gate Option

Description of the Canal

A pictorial view of the scheme is shown in Figure 8-7. Two tide gates are located 6 km and 46 km from the Pacific shore. The gate closer to the Pacific Ocean will be referred to as the South gate, while the one near the Atlantic Ocean will be called the North gate. On the Pacific side, the breakwaters extend to a length of approximately 10 km. However, the breakwaters on the Atlantic side are shorter, 3.5 km long. These values were scaled from the maps, and may be slightly different from the ones proposed. Such minor differences will not alter the modeling results.

The approach canals from the oceans are double lane, 400 m wide, while the 40 km stretch between the gates is single lane, 190 m wide. The inflows from thirteen rivers are shown to enter the canal, while the flows from Trinidad and Ciri are omitted. The stretch of the canal through the Gatun Lake will be diked and, therefore, the inflows from these two rivers are not shown to enter the canal.

To simplify the modeling exercise further, the following assumptions have been made:

PROPOSED SEA-LEVEL CANAL
SCHEMATIC - TIDE GATE OPTION

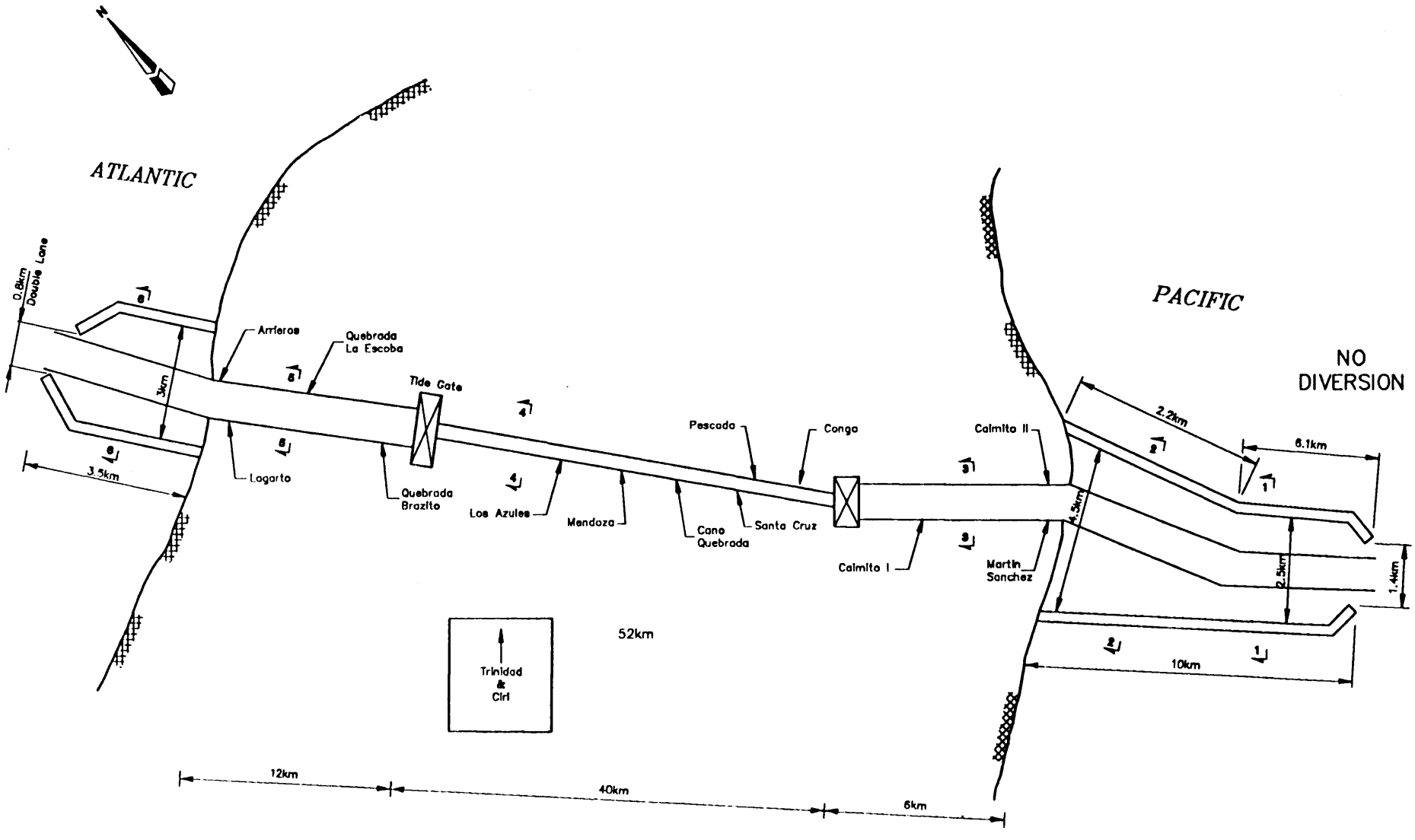


FIGURE 8-7

(a) The canal bed and the side slopes are stable and the material is sand.

(b) The real time operating characteristics of the gates will not be taken into account.

Study Area Links and Nodes

The entire study area, Atlantic approach to the Pacific approach, was represented by 25 links and 26 nodes. The breakwaters in the Atlantic side were represented by 2 links, 225-224 and 224-20, while the breakwaters on the Pacific side were represented by four links, as shown in Figure 8-8. The main canal from shore to shore was represented by 19 links, each approximately 3000 m long. Six typical cross-sections are shown in Figures 8-9 and 8-10. The cross-sections were used to determine channel conveyances and cross-sectional areas. The rivers intercepting the canal were identified by links and are listed on Table 8-3.

Model Simulation

In order to determine the conveyances and cross-sectional areas, model PRELATIS was used. The hydraulic characteristics determined by PRELATIS were used as input to LATIS.

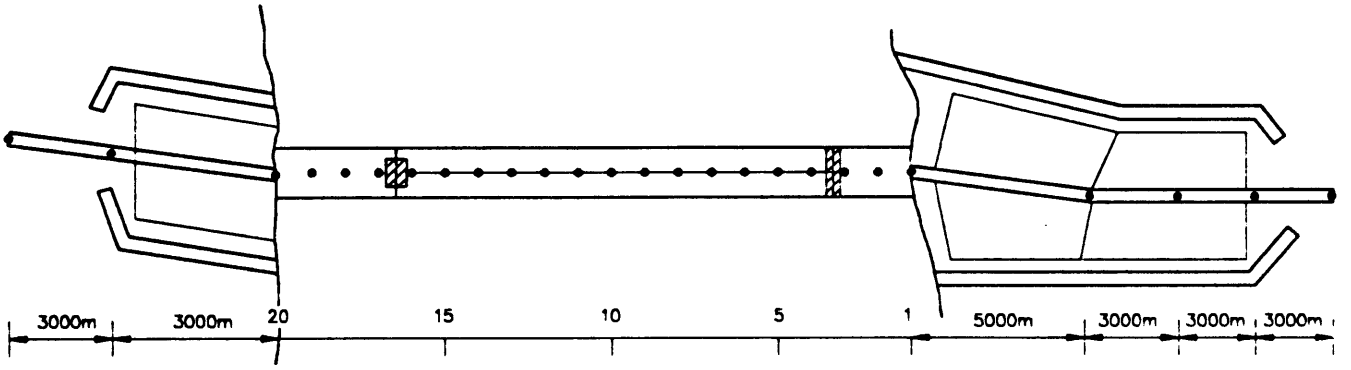
To simplify the effect of opening and closing of the tide gates, two sets of simulations were carried out:

- Assumed that the tide gate at the Atlantic side, North gate, is closed, while the one at the Pacific side is open. Pacific tide controls the movement of sediment.

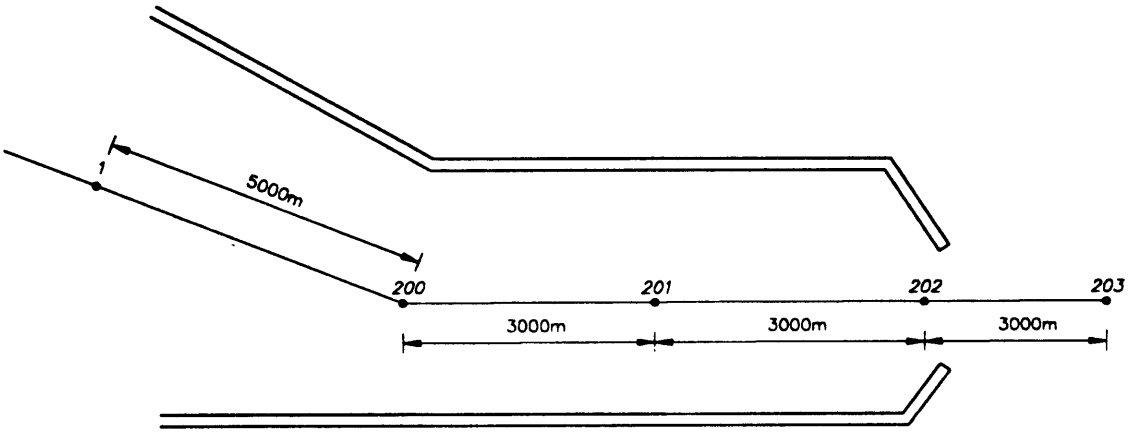
- Assumed that the tide gate at the Pacific side, South gate, is closed while the one at the Atlantic side is open. Atlantic tide controls the transport of sediment.

In running LATIS, depending on which section is being studied, certain links were not included in the modeling. For example, when sedimentation effects on the Pacific side were studied with the North gate closed, links between nodes 225 to 16 were omitted, that is, the stretch of the canal from the Atlantic breakwater to the North gate was not included for modeling. However, when the effects on the Atlantic side were studied with the South gate closed, links between nodes 203 and 3 were omitted, which means the reach from the Pacific breakwater to the South gate was excluded from the modeling study.

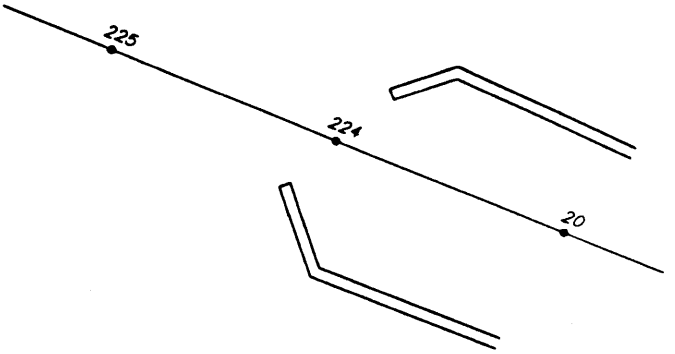
PROPOSED SEA-LEVEL CANAL
MODEL LAYOUT



MODEL LAYOUT



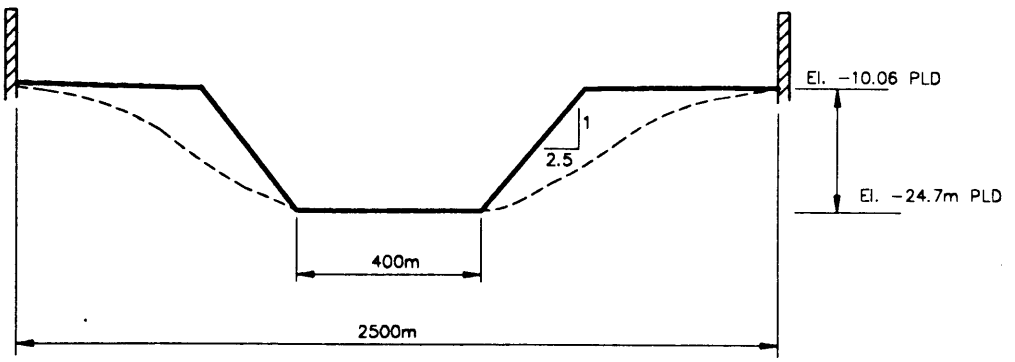
PACIFIC BREAKWATER



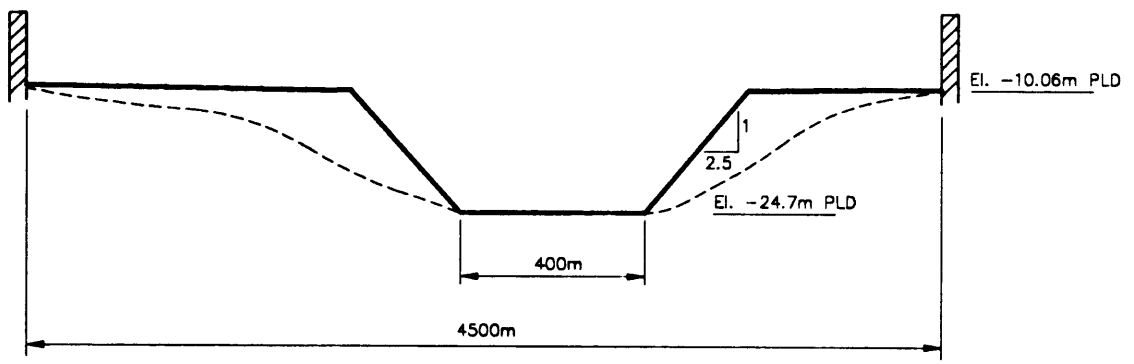
ATLANTIC BREAKWATER

FIGURE 8-8

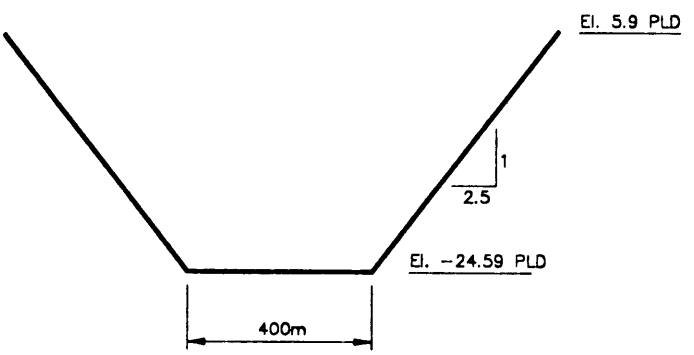
PROPOSED SEA-LEVEL CANAL
IDEALIZED SECTIONS



SECTION 1-1



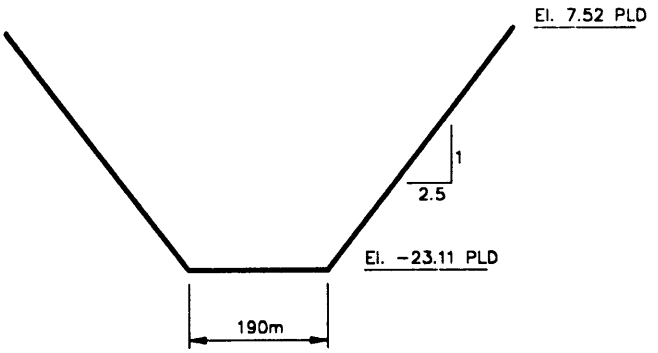
SECTION 2-2



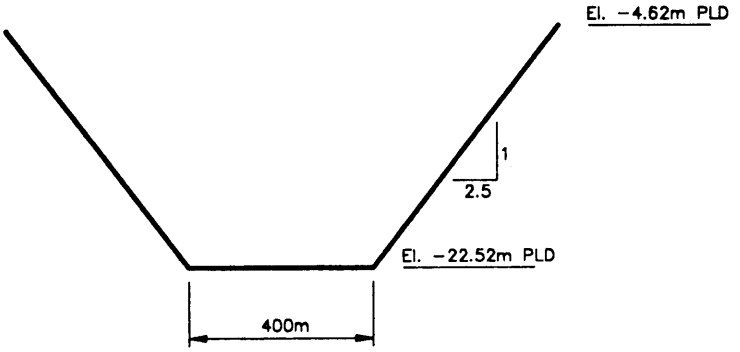
SECTION 3-3

FIGURE 8-9

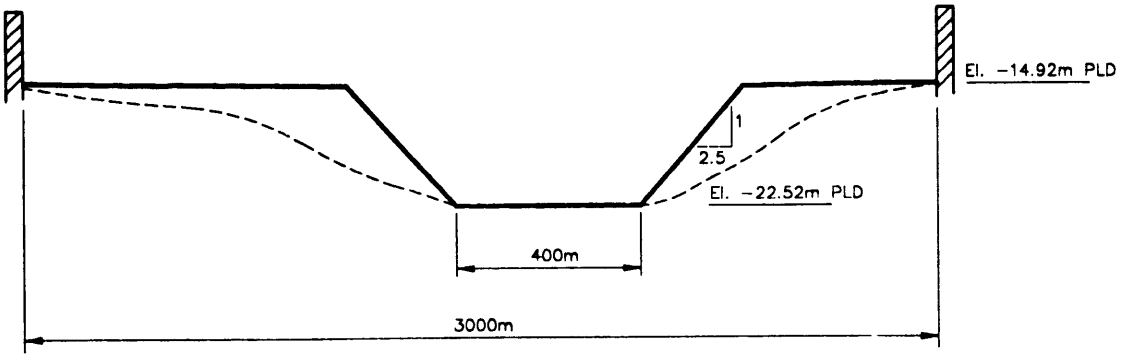
PROPOSED SEA-LEVEL CANAL
IDEALIZED SECTIONS



SECTION 4-4



SECTION 5-5



SECTION 6-6

FIGURE 8-10

TABLE 8-3
PANAMA CANAL FLOWS IN RIVERS

No.	Name	Bank	Link	Max^{m} Flows(cfs)
1	Caimito II	E	101-1	282
2	Martin Sanchez	W	102-1	68
3	Caimito I	W	103-3	693
4	Congo	E	104-5	17
5	Santa Cruz	W	105-6	12
6	Pescado	E	106-8	51
7	Cano Quebrado	W	107-8	172
8	Mondoza	W	108-9	22
9	Quebrada De Chico	W	109-10	25
10	Los Azules	W	110-11	193
11	Trinidad & Ciri	W	111-15	1,728
12	Quebrada Brazito	W	112-17	96
13	Quebrada La Escoba	E	113-18	21
14	Arrieros	E	114-20	204
15	Lagarto	W	115-20	270

As explained at the beginning of this chapter, several physical conditions have to be taken into account. The line diagram in Figure 8-11 shows the several combinations that were considered.

(a) To take into account the diurnal variation of the tide and the spring/neap cycle, the predicted tide for the entire month of January 92 was simulated.

(b) To incorporate the changing flows in the rivers that intercept the canal, three flow conditions, maximum, mean, and minimum were simulated.

(c) To assess the effects due to the type of sediments, coarse sand, fine sand, and clay were analyzed.

(d) And finally, as the sedimentation depths would vary depending on the concentration of sediment carried by the rivers, three values were studied, 5000 mg/l, 2000 mg/l and 100 mg/l.

Model Results

To illustrate the range of sedimentation depths, the results of the following cases are given for the period January 3-13, 1992.

(a) South gate closed, maximum flows in rivers, and sediment composition being coarse sand, in Table 8-4.

(b) North gate closed, maximum flows in rivers, and sediment composition being coarse sand, in Table 8-5.

(c) South gate closed, maximum flows in rivers, and sediment composition being clay as Table 8-6.

(d) North gate closed, maximum flows in rivers, and sediment composition being clay as Table 8-7.

Based on the various simulations that were carried out, the following broad conclusions are made:

(a) When the South gate is closed and the sediment composition is sand, the depth of deposition varies from 0.5 cm to 16 cm per year along the canal for the different nodes

(b) When the North gate is closed and the sediment composition is sand, the depth of deposition varies from 0.5 cm to 100 cm per year at the various nodes.

PROPOSED SEA-LEVEL CANAL
MODEL SIMULATIONS

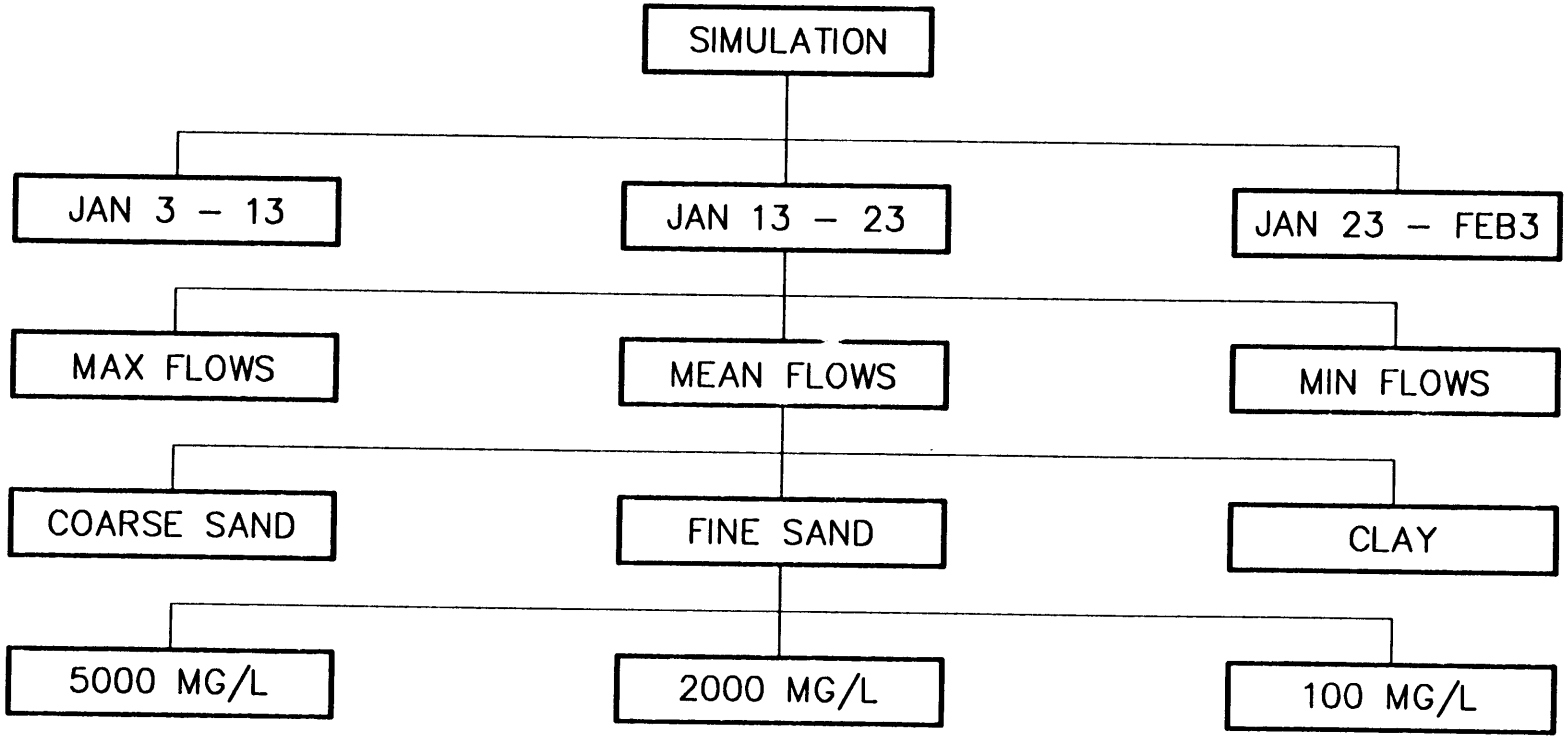


FIGURE 8-11

TABLE 8–4
PANAMA CANAL – SOUTH GATE CLOSED
JAN 3–13, 1992; MAXIMUM FLOWS, COARSE SAND
SEDIMENTATION DEPTHS (FEET)

NODE	295 HOUR	60 HOUR	CHANGE
SEDIMENT CONCENTRATION 100 MG/L			
8	0.0003	0.0000	0.0003
20	0.0001	0.0000	0.0001
SEDIMENT CONCENTRATION 2,000 MG/L			
5	0.0005	0.0001	0.0004
6	0.0004	0.0000	0.0004
8	0.0069	0.0014	0.0055
9	0.0007	0.0002	0.0005
10	0.0068	0.0014	0.0054
15	0.0004	0.0000	0.0004
17	0.0017	0.0003	0.0014
18	0.0004	0.0000	0.0004
20	0.0021	0.0004	0.0017
224	0.0021	0.0004	0.0017
SEDIMENT CONCENTRATION 5,000 MG/L			
5	0.0013	0.0003	0.0010
6	0.0009	0.0002	0.0007
8	0.0173	0.0035	0.0138
9	0.0018	0.0004	0.0014
10	0.0169	0.0034	0.0135
15	0.0009	0.0002	0.0007
17	0.0043	0.0009	0.0034
18	0.0010	0.0002	0.0008
20	0.0053	0.0011	0.0042
224	0.0053	0.0011	0.0042

TABLE 8-5
PANAMA CANAL - NORTH GATE CLOSED
JAN 3-13, 1992; MAXIMUM FLOWS, COARSE SAND
SEDIMENTATION DEPTHS (FEET)

NODE	295 HOUR	60 HOUR	CHANGE
SEDIMENT CONCENTRATION 100 MG/L			
3	0.0007	0.0001	0.0006
8	0.0003	0.0000	0.0003
11	0.0003	0.0000	0.0003
200	0.0002	0.0000	0.0002
202	0.0001	0.0000	0.0001
SEDIMENT CONCENTRATION 2,000 MG/L			
1	0.0012	0.0002	0.0010
2	0.0007	0.0001	0.0006
3	0.0132	0.0027	0.0105
4	0.0010	0.0002	0.0008
5	0.0007	0.0001	0.0006
6	0.0004	0.0000	0.0004
7	0.0004	0.0000	0.0004
8	0.0062	0.0013	0.0049
9	0.0014	0.0002	0.0012
10	0.0046	0.0003	0.0043
11	0.0899	0.0046	0.0853
12	0.0033	0.0001	0.0032
13	0.0002	0.0000	0.0002
15	0.0008	0.0002	0.0006
200	0.0033	0.0007	0.0026
201	0.0009	0.0002	0.0007
202	0.0024	0.0005	0.0019
SEDIMENT CONCENTRATION 5,000 MG/L			
1	0.0031	0.0006	0.0025
2	0.0018	0.0003	0.0015
3	0.0330	0.0067	0.0263
4	0.0026	0.0005	0.0021
5	0.0017	0.0003	0.0014
6	0.0011	0.0002	0.0009
7	0.0010	0.0002	0.0008
8	0.0154	0.0031	0.0123
9	0.0025	0.0005	0.0020
10	0.0020	0.0004	0.0016
11	0.0139	0.0028	0.0111
12	0.0005	0.0001	0.0004
15	0.0019	0.0004	0.0015
200	0.0084	0.0017	0.0067
201	0.0021	0.0004	0.0017
202	0.0060	0.0012	0.0048

TABLE 8–6
PANAMA CANAL – SOUTH GATE CLOSED
JAN 3–13, 1992; MAXIMUM FLOWS, CLAY
SEDIMENTATION DEPTHS (FEET)

NODE	295 HOUR	60 HOUR	CHANGE
SEDIMENT CONCENTRATION 100 MG/L			
5	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0000
8	0.0001	0.0000	0.0001
9	0.0000	0.0000	0.0000
10	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000
15	0.0000	0.0000	0.0000
16	0.0000	0.0000	0.0000
17	0.0000	0.0000	0.0000
18	0.0000	0.0000	0.0000
19	0.0000	0.0000	0.0000
20	0.0000	0.0000	0.0000
224	0.0000	0.0000	0.0000
SEDIMENT CONCENTRATION 2,000 MG/L			
4	0.0000	0.0000	0.0000
5	0.0002	0.0000	0.0002
6	0.0002	0.0000	0.0002
7	0.0003	0.0000	0.0003
8	0.0017	0.0001	0.0016
9	0.0010	0.0001	0.0009
10	0.0018	0.0001	0.0017
11	0.0007	0.0000	0.0007
12	0.0003	0.0000	0.0003
13	0.0001	0.0000	0.0001
14	0.0001	0.0000	0.0001
15	0.0001	0.0000	0.0001
16	0.0001	0.0000	0.0001
17	0.0004	0.0000	0.0004
18	0.0003	0.0000	0.0003
19	0.0002	0.0000	0.0002
20	0.0007	0.0001	0.0006
224	0.0008	0.0001	0.0007
SEDIMENT CONCENTRATION 5,000 MG/L			
4	0.0000	0.0000	0.0000
5	0.0004	0.0000	0.0004
6	0.0004	0.0000	0.0004
7	0.0008	0.0001	0.0007
8	0.0042	0.0004	0.0038
9	0.0026	0.0002	0.0024
10	0.0045	0.0003	0.0042
11	0.0018	0.0001	0.0017
12	0.0008	0.0000	0.0008
13	0.0004	0.0000	0.0004
14	0.0002	0.0000	0.0002
15	0.0002	0.0000	0.0002
16	0.0002	0.0000	0.0002
17	0.0010	0.0001	0.0009
18	0.0007	0.0000	0.0007
19	0.0006	0.0000	0.0006
20	0.0018	0.0001	0.0017
224	0.0019	0.0001	0.0018

TABLE 8-7
PANAMA CANAL - NORTH GATE CLOSED
JAN 3-13, 1992; MAXIMUM FLOWS, CLAY
SEDIMENTATION DEPTHS (FEET)

NODE	295 HOUR	60 HOUR	CHANGE
SEDIMENT CONCENTRATION 100 MG/L			
2	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0000
8	0.0000	0.0000	0.0000
9	0.0000	0.0000	0.0000
10	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000
14	0.0000	0.0000	0.0000
15	0.0000	0.0000	0.0000
16	0.0000	0.0000	0.0000
SEDIMENT CONCENTRATION 2,000 MG/L			
1	0.0001	0.0000	0.0001
2	0.0003	0.0000	0.0003
3	0.0001	0.0000	0.0001
4	0.0001	0.0000	0.0001
5	0.0001	0.0000	0.0001
6	0.0002	0.0000	0.0002
7	0.0003	0.0000	0.0003
8	0.0003	0.0000	0.0003
9	0.0001	0.0000	0.0001
10	0.0001	0.0000	0.0001
11	0.0002	0.0000	0.0002
12	0.0003	0.0000	0.0003
13	0.0005	0.0000	0.0005
14	0.0003	0.0000	0.0003
15	0.0002	0.0000	0.0002
16	0.0001	0.0000	0.0001
200	0.0002	0.0000	0.0002
201	0.0000	0.0000	0.0000
SEDIMENT CONCENTRATION 5,000 MG/L			
1	0.0004	0.0001	0.0003
2	0.0009	0.0002	0.0007
3	0.0003	0.0001	0.0002
4	0.0004	0.0001	0.0003
5	0.0004	0.0001	0.0003
6	0.0005	0.0001	0.0004
7	0.0008	0.0001	0.0007
8	0.0005	0.0001	0.0004
9	0.0001	0.0000	0.0001
10	0.0002	0.0000	0.0002
11	0.0004	0.0000	0.0004
12	0.0006	0.0000	0.0006
13	0.0008	0.0000	0.0008
14	0.0005	0.0000	0.0005
15	0.0003	0.0000	0.0003
16	0.0002	0.0000	0.0002
200	0.0004	0.0001	0.0003
201	0.0000	0.0000	0.0000
202	0.0000	0.0000	0.0000

(c) When the South gate is closed and the sediment consists of clay, the annual deposition varies between zero to 5 cm along the canal.

(d) When the North gate is closed and the sediment consists of clay, the annual variation is from zero to 5 cm along the canal.

As far as the annual dredging is concerned, it can be in the range of 450,000 m^3/yr corresponding to an annual sedimentation of 2.5 cm in the entire stretch of the canal. According to the model results, the value reduces to 270,000 m^3/yr corresponding to an annual sedimentation of 2 cm in the entire length, when rivers are diked. However, judgment has to be exercised in the use of these results due to the various approximations that have been used in the model.

Lock Alternatives (The Canal Zone)

In these alternatives, there is only one structure, a lock at 6 km from the Pacific shore as shown in Figure 8-12. The reach of the canal from the lock to the Atlantic is a single lane canal, 190 m wide. The conclusions that we have arrived at in the Tide Gate Alternatives regarding the canal itself also apply to the lock alternatives.

The Coastal Zone

The construction of breakwaters alters the movement of sediment along the coastline. The accretion and depletion of beaches along the coast, due to the construction of the breakwaters, were studied by the model BEACHES.

Schematics of Shorelines and Structures

Figures 8-13 and 8-14 show schematics of the shorelines and the breakwaters for the purpose of modeling the evolution of the beach resulting from the proposed breakwaters. Figure 8-13 shows the Atlantic entrance jetties and Figure 8-14 shows the Pacific entrance jetties. For modeling, the shorelines have been assumed to be rectilinear. As shown in Figure 8-13, the rectilinear assumption of shorelines in the Atlantic shores is reasonable. Lengths of the breakwaters on this side are 2.7 and 2.58 km. Therefore, a 2.6-km long structure length is assumed to represent the Atlantic jetties. An 8-km left shore and a 10-km right shore, as shown in Figure 8-13, are taken for shoreline evolution modeling on the Atlantic side.

Although the right Pacific jetty is 7.5 km long, only 5.5 km is in water. The balance 2-km length near the shore is in mud. The left Pacific jetty is 2.5 km long, and its projected length with the 2.4 km hammer head is 4.5 km. Therefore, a structure length of 5.0 km is assumed to represent the Pacific jetties. A 14-km shoreline on the left side and a 14-km shoreline on the right side, as shown in Figure 8-13, are taken for modeling. The shorelines have been assumed to be straight and the

PROPOSED SEA-LEVEL CANAL
SCHEMATIC - LOCK OPTION

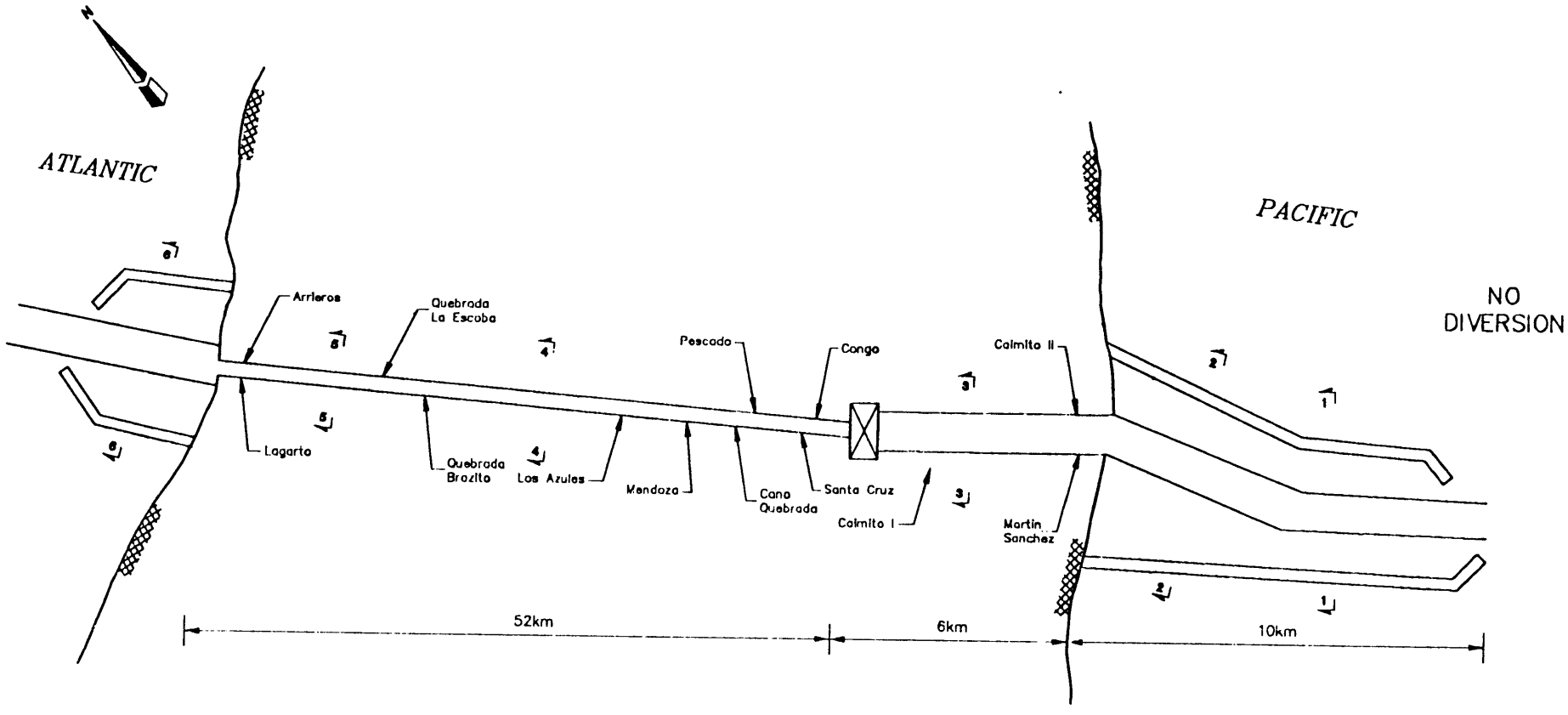


FIGURE 8-12

PROPOSED SEA-LEVEL CANAL
SCHEMATIC FOR BEACHES - ATLANTIC

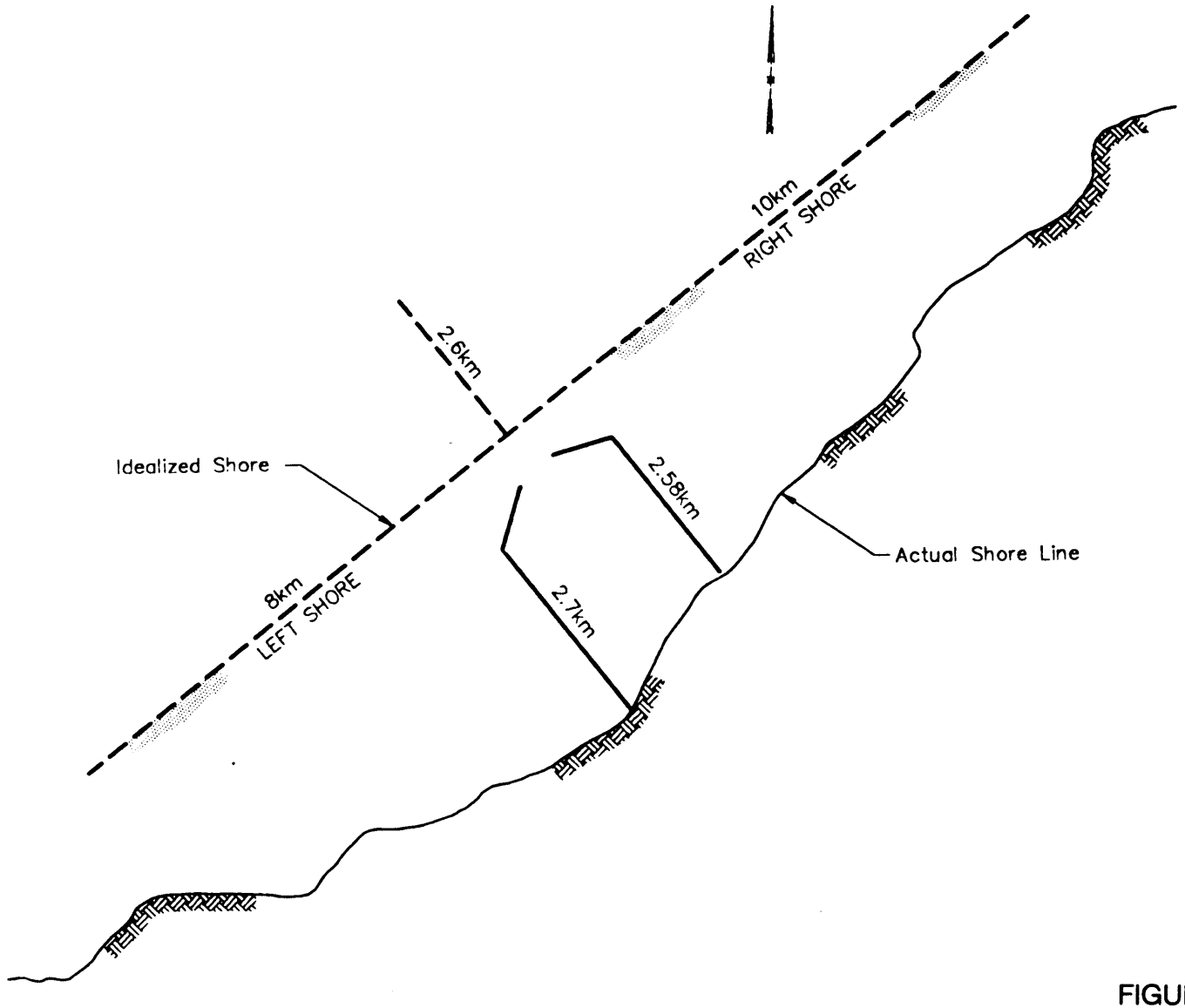


FIGURE 8-13

PROPOSED SEA-LEVEL CANAL
SCHEMATIC FOR BEACHES - PACIFIC

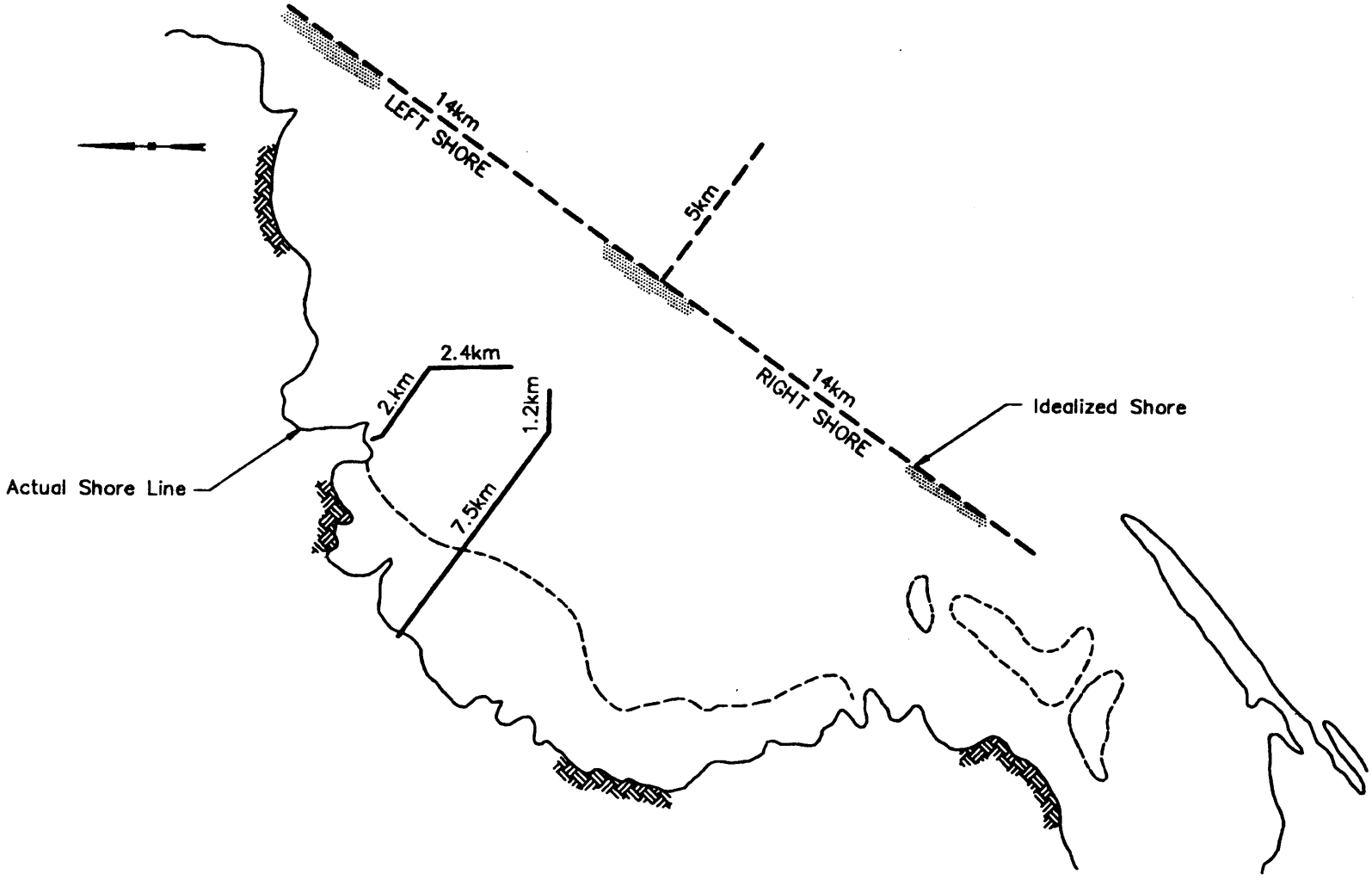


FIGURE 8-14

shoreline space increment has been taken as 1.0 km. A time increment of 15 days and an active beach depth of 5m (15 ft) have been assumed.

Wave and Wind Data

Wave and wind data were obtained from the National Climatic Data Center, Asheville, North Carolina. The five-year wave/wind data, each having 30,000 to 40,000 lines of record, were processed to isolate the wave data (one year of these data [year 1984] are presented in Appendix K). These data covered most of the Caribbean Sea and some parts of the Pacific Ocean. For modeling the Atlantic side of the canal, waves were isolated between latitudes 9-15 degrees, and longitudes 75-84 degrees. For modeling the Pacific side, waves from latitudes 7-9 degrees and longitudes 77-81 degrees were isolated. Since these were deep water waves, and while approaching the shore these waves would lose strength, a coefficient of 0.1 was used to compute the effective waves along the shorelines.

Model Results

The model results must be considered as a qualitative indication of accretion and depletion. For a more quantitative estimate, the model parameters must be calibrated using historical measurements of an existing beach accretion and depletion case near the project location.

Atlantic Jetties

Figure 8-15 shows results of the beach evolution model on the Atlantic side of the canal. Wave analysis showed stronger waves from the left side of the jetties and, therefore, accretion is predicted on the left side. As expected, depletion is predicted on the other side, the right hand side of the jetties.

This indicates net littoral drift from left to right on the Atlantic shore of the canal. Onshore waves were found in 498 days in 5 years, and the model computed yearly representative (littoral drift producing) waves of 1.4m (4.6 ft) for a period of 75 days from the left in comparison to 1.2m (3.8 ft) of waves for a period of 15 days from the right. With all the assumptions and approximate parameters, the model predicted an accretion of 1 km on the left of the jetties and a depletion of 600 m on approximately 11 km from the right jetty in ten years.

Pacific Jetties

With the same parameters, the model computed yearly representative (littoral drift producing) waves of 1.0m (3.4 ft) for a period of 15 days from the left side of the Pacific Jetties and 1.2m (3.8 ft) for the same period from the right side. Since the waves from both sides are approximately equal, the

BEACH EVOLUTION MODEL RESULTS
ATLANTIC

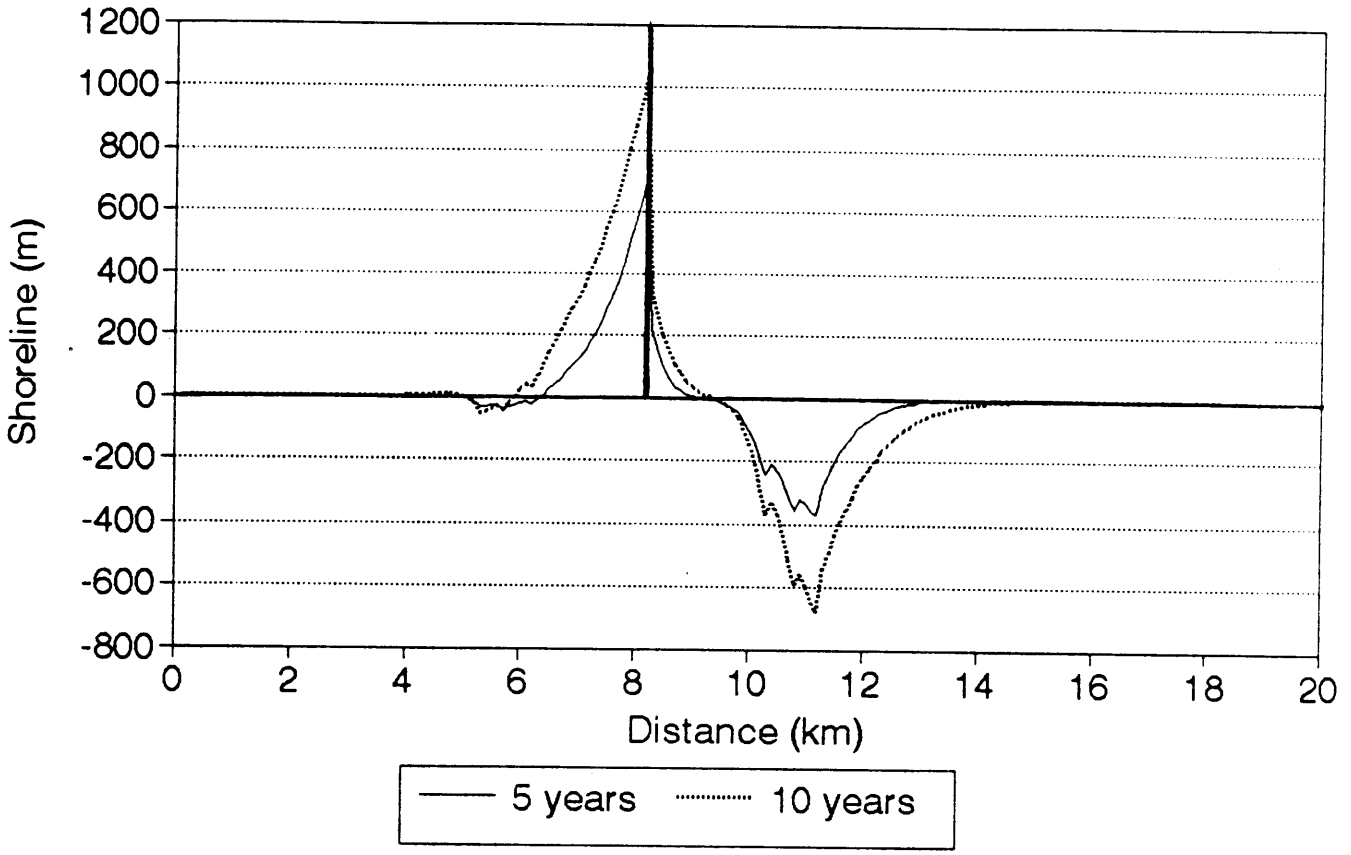


FIGURE 8-15

model computed zero net littoral drift, and thus, did not predict any accretion or depletion on either side. However since the waves from the right side are a little stronger, some accretion on this side and some depletion on the left side may be expected. Also, this side of the canal entrances is protected by peninsulas and shoals, and therefore, severe accretion and depletion are unlikely.

Sedimentation in the Existing Canal

As the model predicted sediment depths were based on several assumptions and approximations, it was decided to compare the predicted depths of sedimentation with the actual sedimentation that had occurred in the existing canal. The intention was to determine how well the predicted values compared with the measured values; (i.e., were they within the same order of magnitude or not) and also to estimate sedimentation for the high rise canal.

The data were obtained from hydrographic surveys, conducted at the same location, at different periods of time. Care was taken to ensure that no dredging took place at the selected locations during the intervening period between the two surveys. To estimate the amount of sedimentation, reaches of specific lengths were selected. Numerical integration was used to estimate the volume of water below a datum. The change in the volume of water between the two survey periods gave the quantity of sediment either deposited or eroded. The location of the reaches, the lengths, the survey dates, and the quantity of sediment deposited over a 150 m (500 ft) wide canal is tabulated below:

Location	Reach	Period	Quantity of Sediment m^3
Atlantic Entrance	1028+000 to 1030+500(m)	6-85 to 1-88	46,985
Balboa Inner Harbor	2380+00 to 2400+00 (ft)	7-85 to 4-87	15,360
Pacific Entrance	2550+00 to 2570+00 (ft) 2740+00 to 2760+00 (ft)	6-85 to 3-87 7-85 to 1-87	23,920 4,760
Miraflores Lake	2140+00 to 2160+00 (ft)	1-87 to 10-91	20,659

SUMMARY AND CONCLUSIONS REGARDING SEDIMENT TRANSPORT

Several computer programs were used in the study. Each one had a unique application, namely,

- LATIS — to determine hydraulic variables such as velocity, water depth, and create the necessary input data for ROUTES;

- ROUTES to estimate sedimentation depths along the canal with the output from LATIS;

- BEACHES to estimate shoreline changes.

The models, which are idealizations of the physical process, give estimates which have to be interpreted with judgment. This is due to the underlying assumptions in the model, input data, boundary conditions, and the numerical scheme used in the algorithm. The values of several parameters were assumed, based on available literature and engineering judgment.

The following broad conclusions can be arrived at:

(a) The model indicated that annual dredging in the canal section between the coasts for the tide gate and lock alternatives would be in the range of 450,000 m^3/yr, due to the effects of sediment inputs from the rivers and the tidal transport. In the absence of river sediments, the model results indicated a 30% reduction in the quantity of sediment to be dredged.

(b) Bathymetric data were used to estimate sedimentation rates for the existing canal. The locations, the annual sedimentation rates per kilometer and the extrapolated values for a canal of 58 km long are summarized below.

	Sediment Deposition/Year	
	190m Wide Canal (m^3/km)	58 km Stretch (m^3)
Atlantic Entrance	9,500	551,000
Balboa Inner Harbor	12,800	742,000
Pacific Entrance	11,850	687,300
Miraflores Lake	9,550	--

Based on the above table, a mean sedimentation rate of 660,000 m^3/yr is an acceptable value.

(c) On the Atlantic side, the model predicted an annual littoral drift of 12 x 10^6 m^3/year. This would result in an accretion on the southern breakwater of 100 m, while the depletion on the northern breakwater is 60 m per year. In other words, the shoreline adjacent to the southern breakwater moves outward along the breakwater at the rate of 100 m per year building up a beach from the trapped littoral drift. At this rate, with the length of the breakwater being 2.6 km, it will be 25 years or so after construction before any of the material transported by littoral currents enter the canal.

(d) The model predicted neither accretion nor depletion on the Pacific side. However, some accretion and depletion are expected. Climatic data, especially very close to the site, should be collected and a detailed study conducted.

It should be noted that the model results are qualitative and for the present time, are reasonably accurate. For planning and estimation of annual dredging costs one could use a value of 550,000 m^3/year.

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CHAPTER 9

NAVIGATION SUPPORT SYSTEMS

GENERAL CRITERIA - HIGH-RISE LOCK CANAL AND SEA-LEVEL CANAL

Channel Range Lights

For the High-Rise Lock Canal, range lights for the new channels (Alternatives 2 through 7) should be provided in the same manner as the present Panama Canal channels.

For the Sea-Level Canal the following lighting should be provided:

Leading Channel Range Lights should be provided throughout the canal channels. Excessively long stretches of straight channel should be avoided by having a small turn of 7 or 8 degrees every five miles or so to make possible these leading channel range lights. In portions wide enough for two-way traffic, there should also be passing ranges.

The one-way portions of the canal should have, at about every 500 feet (152 meters), fixed red lights on the west side and fixed green on the east side from the Atlantic entrance as far south as the Pacific tidal gates (or locks) with the lighting pattern reversed at that point. At the turns, the lights should be flashing.

In the two-way channels, there should be buoys or beacons on each side of the channel at least every half nautical mile (927 meters) lighted in the same manner as the bank lights. USCG specifications state that such buoys in the straight stretches should have occulting lights but fixed lighting is better for judging channel alignment from the bridge of a ship.

For both types of canal, state-of-the-art navigation aids should be supplied to aid pilots during periods of poor visibility. Radar aboard transiting ships can not be counted on for this purpose.

Conceptual plans of the navigation aids appear in Figures 9-1, 9-2, 9-3 and 9-4.

GENERAL REQUIREMENTS FOR TUGS

Tug assistance should be provided on the bow of all vessels over 15,000 DWT as they approach locks or closed tidal gates. Additional tugs should be available to assist when special circumstances or emergencies require.

Tugs scheduled to assist vessels over 75,000 DWT should be at least 6,000 hp and of the "tractor" type, which are capable of approximately equal thrust in all directions.

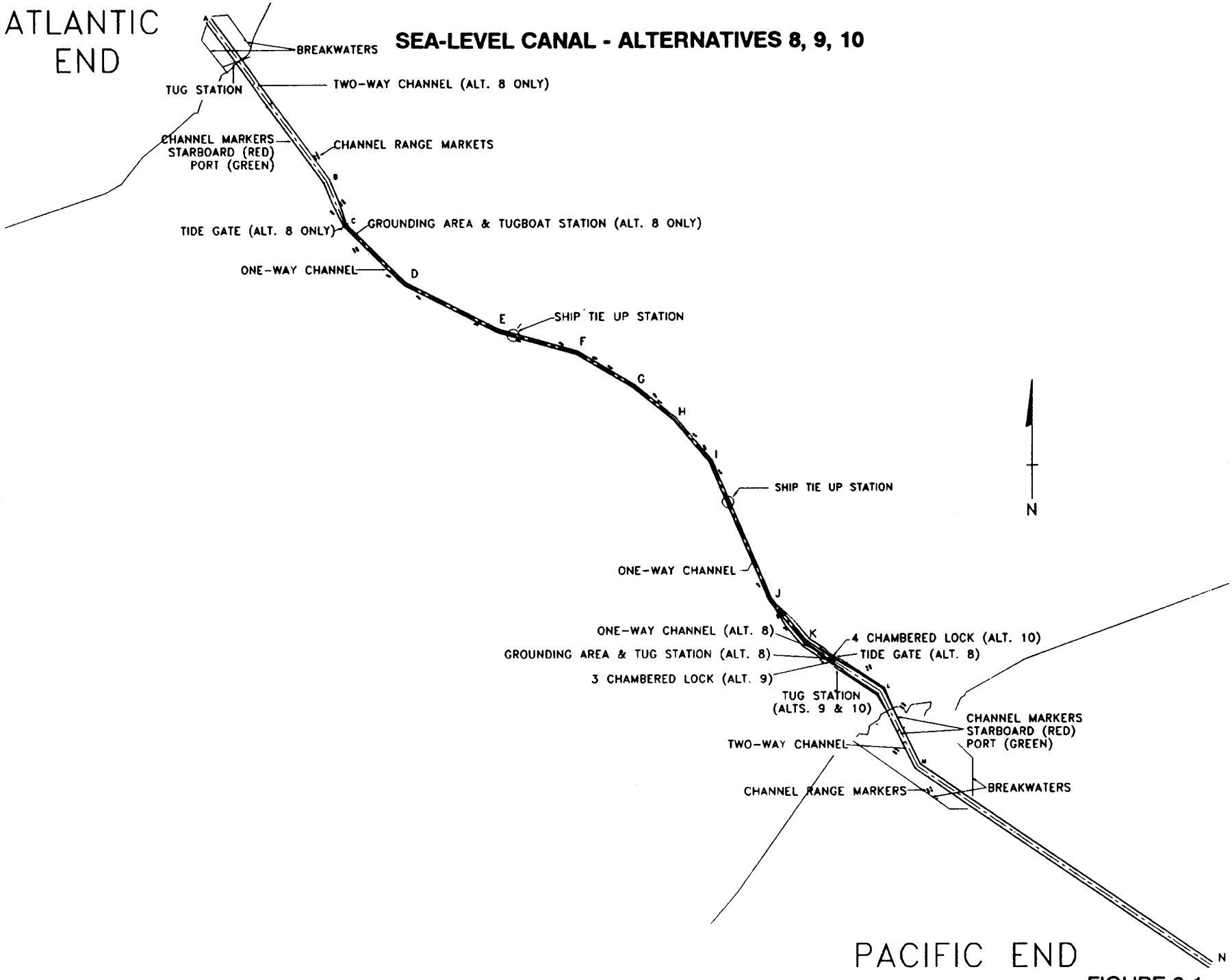
ATLANTIC END
SEA-LEVEL CANAL - ALTERNATIVES 8, 9, 10
BREAKWATERS
TUG STATION
TWO-WAY CHANNEL (ALT. 8 ONLY)
CHANNEL MARKERS
STARBOARD (RED)
PORT (GREEN)
CHANNEL RANGE MARKETS
B
C
TIDE GATE (ALT. 8 ONLY)
GROUNDING AREA & TUGBOAT STATION (ALT. 8 ONLY)
ONE-WAY CHANNEL
D
E
SHIP TIE UP STATION
F
G
H
I
SHIP TIE UP STATION
N
ONE-WAY CHANNEL
J
ONE-WAY CHANNEL (ALT. 8)
K
4 CHAMBERED LOCK (ALT. 10)
GROUNDING AREA & TUG STATION (ALT. 8)
TIDE GATE (ALT. 8)
3 CHAMBERED LOCK (ALT. 9)
TUG STATION
(ALTS. 9 & 10)
CHANNEL MARKERS
STARBOARD (RED)
PORT (GREEN)
TWO-WAY CHANNEL
CHANNEL RANGE MARKERS
BREAKWATERS
PACIFIC END
N

FIGURE 9-1

ATLANTIC END - SEA-LEVEL CANAL - ALTERNATIVE 8

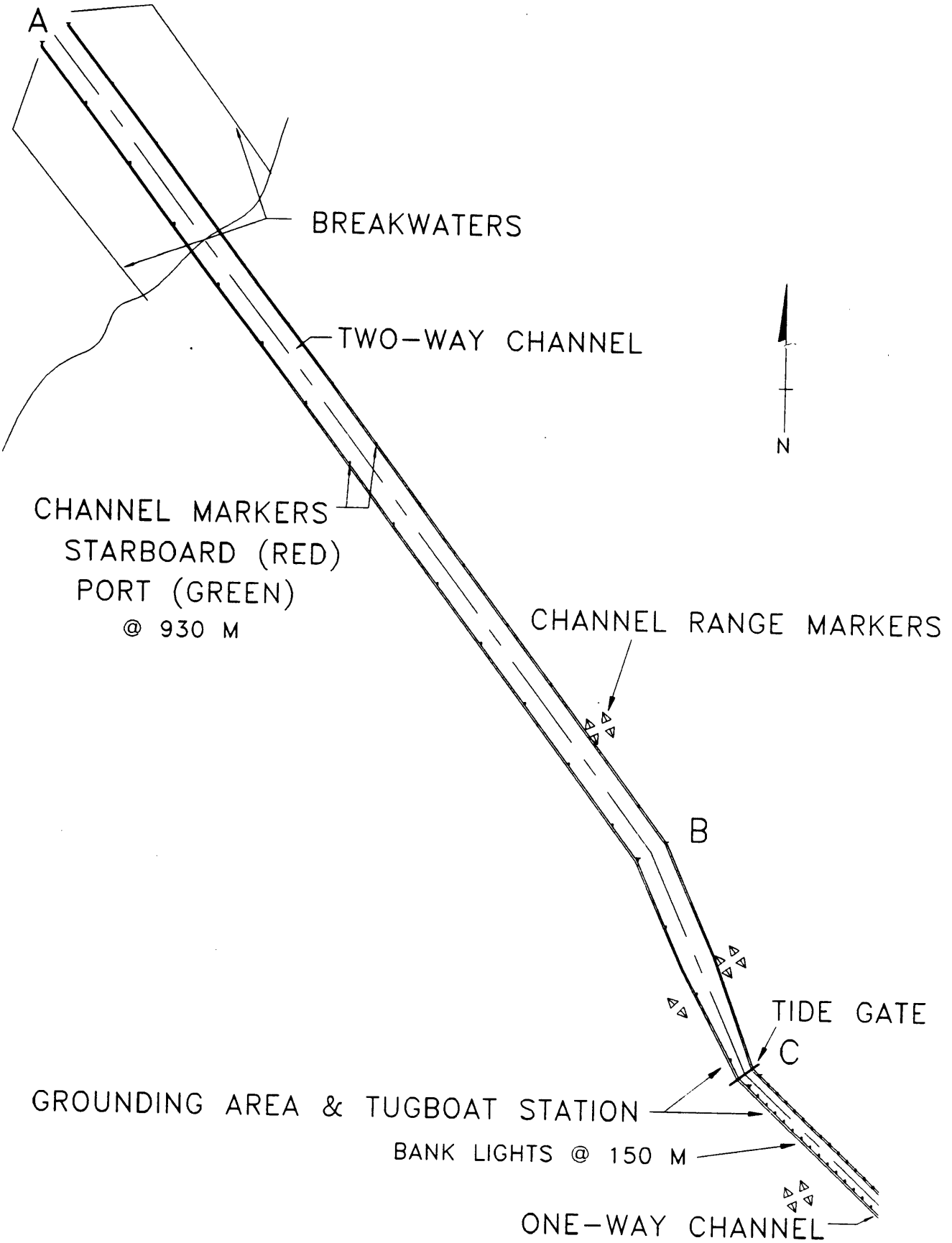

FIGURE 9-2

PACIFIC APPROACH - SEA-LEVEL CANAL - ALTERNATIVE 8

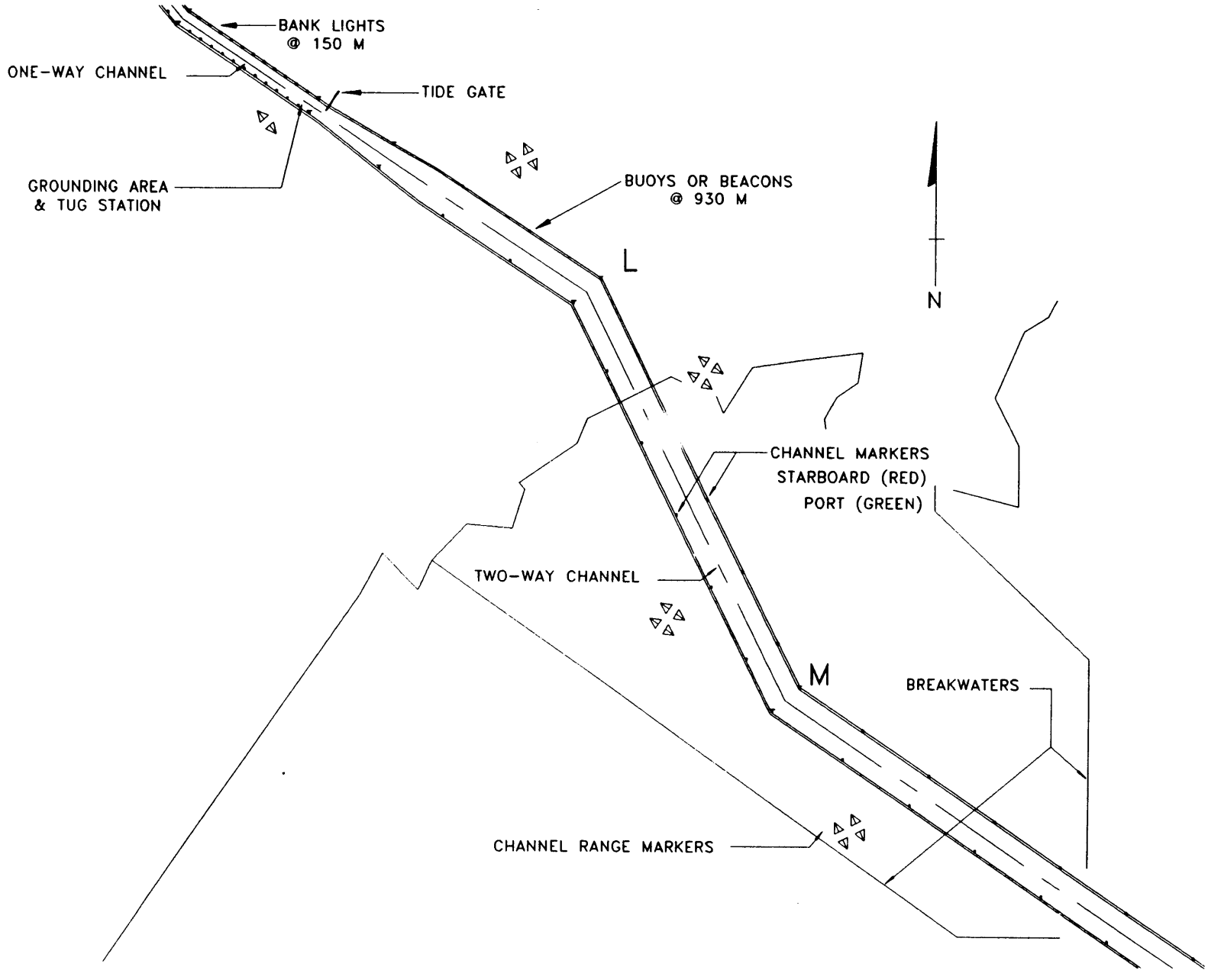

FIGURE 9-3

PACIFIC APPROACH - SEA-LEVEL CANAL - ALTERNATIVES 9 & 10

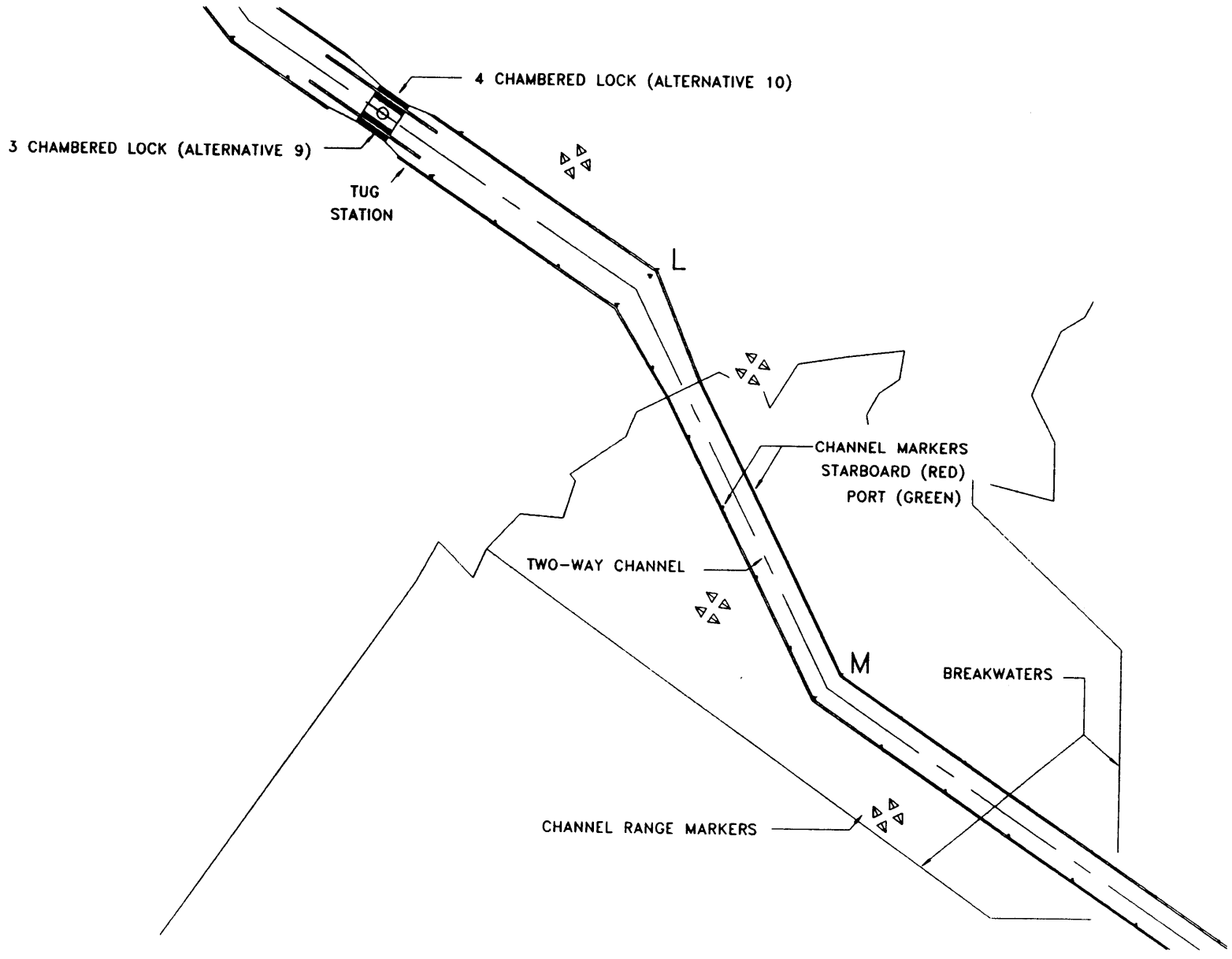

FIGURE 9-4

All tugs should be equipped, and the crews trained, for fighting fires.

Vessels transiting narrow channels should be provided with a tug on the stern (Culebra Cut style) if they equal or exceed the following tonnages:

- Culebra Cut: one-way channel - 50,000 DWT;
- Culebra Cut: two-way channel - 100,000 DWT;
- Sea-Level Canal: one-way channel - 75,000 DWT.

It should be a transit requirement that such vessels be constructed with sterns that allow a tug to work there on the center line when deeply loaded.

GENERAL REQUIREMENTS FOR THE NEW HIGH-RISE LOCKS (85 FT) -- ALTERNATIVES 2 THROUGH 7

The approach walls at both ends of both locks (Atlantic and Pacific) should be at least 1,500 feet (457 meters) long with locomotive tracks extending, as far as practical, to the end of the wall to facilitate timely and safe lock entry for large ships.

With proper fendering and sufficient lock width, it may be feasible to operate the new locks with locomotives on one wall only. Locomotive tracks should be constructed on the opposite wall, at least on the first lock lane put into service, in case this does not work out in practice.

Tug assistance should be provided for lock approach and entry, as follows:

1 tug - all vessels over 25,000 DWT;

2 tugs - all vessels over 30,000 DWT at the Pacific Locks southbound and all vessels over 35,000 DWT for other locks and directions;

3 tugs - all vessels over 75,000 DWT.

Strict traffic control will have to be exercised at the points of convergence of the original and new canal channels, particularly where they join in the Culebra Cut north of Pedro Miguel Locks.

HIGH RISE LOCKS (85 FT) 150,000 AND 200,000 DWT, SINGLE-LANE LOCKS, CULEBRA CUT TWO-WAY -- ALTERNATIVES 2 AND 4

To equip the canal with the locks operating at capacity would require at each of the two locks (Atlantic and Pacific) ten locomotives for one-wall operation (allowing two down for maintenance) and twice that number for two-wall operation.

Seven 6,000 hp (minimum power) tugs would cover the maximum needs at the Pacific locks and the Cut and five tugs could handle these needs at the Atlantic

locks. Allowing for three down for maintenance, a total of 15 tugs of 6,000 hp or greater would be required, building up to 19 tugs at capacity, in addition to the tug fleet needed to operate the original locks.

With the Culebra Cut handling two-way traffic, additional tie-up facilities at the north end of the Pacific locks would not be required and ships would have more expeditious transits.

HIGH-RISE LOCKS (85 FT) 150,000 AND 200,000 DWT, DOUBLE-LANE LOCKS, CULEBRA CUT TWO-WAY -- ALTERNATIVES 3 AND 5

To equip the canal to operate these locks at capacity would require at each of the two locks (Atlantic and Pacific ends) 19 locomotives for one-wall operation (allowing for three down for maintenance) and twice the number for two-wall operation.

Eight 6,000 hp (minimum power) tugs would cover the needs at the Pacific locks and the Cut and six tugs could handle the needs at the Atlantic locks. Allowing for three down for maintenance, this would require a total of 17 tugs of 6,000 hp or greater, building up to 23 tugs at capacity, in addition to the tug fleet needed to operate the original locks.

Additional tie-up facilities at the north end of the Pacific locks would not be required.

HIGH-RISE LOCKS (85 FT) 150,000 AND 200,000 DWT, SINGLE-LANE LOCKS, CULEBRA CUT ONE-WAY -- ALTERNATIVES 6 AND 7

Ship tie-up facilities should be provided at the north end of the new Pacific locks for ships awaiting the passage of southbound clear-cut ships.

The safest and most rapid tie-up facility would be an approach wall on the north end of the locks long enough for two large ships to tie up after locking through. The wall should be at least 2,400 feet (732 meters) in length. Locomotive tracks should extend to as near the end as practical. While this arrangement allows for rapid tie-up, it blocks one lane from being used for traffic in the opposite direction.

There should also be at least two additional tie-up berths close to the north end of the new Pacific locks. Using these additional berths will be time consuming due to the slow speed with which these ships have to be handled. Also, the mooring facilities must be sturdy enough to hold the ships in place while other very large displacement vessels pass near them in these confined spaces.

To equip the canal to operate these locks at about capacity would require, at each of the two locks (Atlantic and Pacific ends), 10 locomotives for one-wall operation (allowing for two down for maintenance) and twice that number for two-wall operation.

Seven tugs should be able to handle the Pacific locks and the Cut and five tugs could handle the needs at the Atlantic locks. Allowing for three down for maintenance, a total of 15 tugs of 6,000 hp or greater would be required, building up to 19 tugs at capacity. This would be in addition to the fleet of tugs required to operate the original locks.

SEA-LEVEL CANAL - GENERAL PROVISIONS

Beaching areas should be provided at about five mile intervals. These distances can vary when the topography so requires.

Two emergency tie-up stations should be provided in the one-way central portion of the canal, one at about one-third length intervals from each end. These locations can also serve to station tugs on emergency standby duty.

Tug stations should also be maintained near the Locks or Tide Gates.

SEA-LEVEL CANAL WITH TIDE GATES 40 KM APART
HALF-TIDE OPERATIONS, 250,000 DWT -- ALTERNATIVE 8

The operating speed for laden ships over 75,000 DWT in the canal would be 13 kph (7 kts), which is the most rapid practical and reasonably safe speed for large vessels to proceed through narrow channels with a tug made fast on the stern (Culebra Cut style).

The lead ship of each convoy should enter the 40 km long Canal section between the tide gates about two hours and 42 minutes before the tide gate at the opposite end is due to open. At 13 kph (7 kts), this would place the vessel about five km (2.7 nautical miles) from the gate at the time it was due to open. Each convoy could be up to 35 km (18.9 nautical miles) in length.

Based on the traffic projections for the year 2020, a fleet of five tugs should be sufficient to handle the channel traffic. In addition to this, about four tugs should be on standby duty (at the two ends of the canal and at the two tie-up stations) to assist as needed and tugs should be assigned to standby to assist at least the two lead ships of each convoy as they approach the closed tide gate. Allowing for three tugs being down for maintenance, a total of fourteen tugs would be required. AT least nine of these should be 6,000 hp or greater and the others could be 3,000 to 4,000 hp.

Anchorages should be provided at the sea entrances at each end of the canal.

It is essential that the tide gates be operated at a time when the water height is equal at both sides of the gates. If the correct time is missed and the gates could not be closed against the current, there could be significant negative consequences.

Back-up tide gates should be provided to assure that currents and channel depths are controlled in the event of a failure of a gate to close.

The undesirable migration of sea life between the oceans should be prevented. If a fresh water barrier from side streams is used, any significant proportion of fresh water would require a deeper channel to allow for deeper freshwater drafts.

SEA-LEVEL WITH PACIFIC LOCKS, ROUTE 10
250,000 DWT -- ALTERNATIVES 9 AND 10

Locks should be designed in units of two lanes each, with adequate separation between the units to allow for safe approach and exit of ships.

Locks preferably should be angled about 10° to the right of the channel alignment to aid single screw ships in approach and entry.

The concept of Pacific locks, to adjust to tidal differences, would eliminate the necessity of having to schedule ships according to the tidal cycles. The length of time that the canal would operate southbound and northbound could be adjusted to best suit the actual arrivals, and provide maximum capacity.

The area of the canal north of the Pacific locks would be operated at the level of the Atlantic end which only varies about two feet (0.6 meters) at spring and one foot (0.3 meters) at neap tides. Tidal currents in the canal north of the locks would be negligible.

The Pacific tides have a maximum spring tidal range of about 21 feet (6.4 meters) and the neap tidal range is about eight feet (2.4 meters). High water occurs on the Pacific side about three hours after high water at the Atlantic side of the isthmus. Therefore, the greatest adjustment needed at spring tide is about 22 feet (6.7 meters), which translates to up or down about 11 feet (3.4 meters) from the Canal Operating Level. The average tidal range would be about 15 feet (4.6 meters) or about 7.5 feet (2.3 meters) up or down. The average lockage would be half of that or about 3.75 feet (1.14 meters).

To facilitate a change in direction of canal traffic without unduly delaying ships, it would be a desirable practice to "stack up" a few northbound ships in the area just north of the locks while the one-way canal channel is operating southbound. Another lock with one lane would suffice for the purpose of "stacking up" three large northbounds (or more smaller ships). This could be done during the last hour or two while southbound traffic was proceeding through the one-way portion of the canal. The north approach walls should be at least 2,400 feet (732 meters) in length so as to provide easy and rapid tie-up for two large (or more smaller) ships. Locomotive tracks should extend to as near to the extreme end of the wall as practicable. An additional lockage could be held in the chamber.

If another lock with only one lane is to be built, it should be laid out in such a way as to allow easy conversion to a two-lane lock at a later date should that prove to be necessary; for instance, in connection with widening the canal channel for two-way traffic. To allow for the safe and timely entry of large ships, the south approach walls should be at least 1,500 feet (457 meters) in length with locomotive tracks extending as near to the extreme end of the wall as practicable.

With proper fendering and sufficient lock width, it may be possible to operate these locks with locomotives on one wall only. Locomotive tracks should be built into the other wall, at least on the first lock lane put into operation, in case this does not work out in practice. The type of locomotives used in the present Canal should be suitable. For one-wall operation, eight working locomotives should be supplied for each operating lane at the locks plus two spares for maintenance down time. For two-wall operation, twice as many locomotives will be required.

The channel at the lock approach (on both ends) should be at least 2,000 feet (610 meters) wide for at least three Km to facilitate two-way traffic, the slowing of ships and their maneuvering to enter and exit the locks.

Tug assistance should be provided for lock approach and entry, as follows:

1 tug - all vessels over 25,000 DWT;

2 tugs - all southbound vessels over 30,000 DWT and northbound vessels over 35,000 DWT;

3 tugs - all vessels over 75,000 DWT.

Based on projected ship mixes, a fleet of eight tugs should be sufficient to handle the channel traffic. In addition to this four tugs should be on standby duty (at the two ends of the canal and at the two tie-up stations) to assist, as needed, and about seven tugs would be required to assist ships at the locks. Allowing for four tugs being down for maintenance, a total of 23 tugs would be required. About 16 of these should be 6,000 hp or greater and the others could be 3,000 to 4,000 hp.

As in the case of Alternative 8, the undesirable migration of sea life between the oceans should be prevented.

CHAPTER 10

CAPITAL AND OPERATING COSTS OF NAVIGATION SUPPORT SYSTEMS

ESTIMATES OF QUANTITIES

Based on the criteria set forth previously herein, Table 10-1 lists the type and quantities of navigation aids and equipment required in the alternative plans (designated as Alternatives 2 through 10) being compared in this study for transiting of large ships across the Isthmus. The items listed for the Alternatives are in addition to the quantities, also listed in Table 10-1, entailed in the Status-Quo Program (Scenario 1), of which are either already in place or will be before the year 2020. The status quo data are required for the preparation of annual maintenance and operating costs.

The estimates are based on data on the existing canal furnished by PCC and the navigation support systems for the aternatives outlined in Chapter 9.

The number of tugboats listed in Table 10-1 are for the levels of ship traffic projected in the year 2020. In subsequent years, when traffic is expected to increase, additional tugboats will have to be provided, and this should be considered in the financial analyses to be made by others. Of the quantities listed for tugboats in Table 10-1, 20 percent comprise spares for use in emergencies or are stand-by units to be used when other units are being overhauled or undergoing maintenance. For similar purposes, 15 percent of the towing locomotives listed in Table 10-1 consist of emergency or stand-by units. This distinction of operating and spare units is made for use in estimating subsequently the annual costs entailed in the scenarios.

ESTIMATED VALUES AND CAPITAL COSTS

Summarized in Table 10-2 are the additional capital costs for providing such equipment in Alternatives 2 through 10. Details of the estimates are given in Table 10-3.

The costs are given in Tables 10-2 and 10-3 for both one-wall operations and separately for two-wall operations at the locks to be constructed in the alternative scenarios, the latter entailing a greater number of towing locomotives.

The figures in Tables 10-2 and 10-3 are for a three-shift per day operation of the locks in all scenarios, and include an allowance of 20 percent for contingencies and engineering. The costs for facilities such as locks, tidal gates, tugboat tie-up stations, beaching areas, turning basins and other dredging works, buildings for traffic management operations and pilot lodging quarters are not included herein.

TABLE 10-1
NAVAIDS AND EQUIPMENT REQUIREMENTS - QUANTITIES

Item	Unit	Status Quo	Additional Quantities - Alternatives								
			2	3	4	5	6	7	8	9	10
1. Channel Navaids											
a. Range Lights	each	188 (a)	206 (b)	206 (b)	206 (b)	206 (b)	206 (b)	206 (b)	64	60	60
b. Bank Lights (1 lane)	each	-	-	-	-	-	-	-	530	694	694
c. Bank Lights (2 lanes)	each	164 (a)	174 (c)	174 (c)	174 (c)	174 (c)	174 (c)	174 (c)	52	20	20
d. Lighted Buoys	each	70 (a)	70 (a)	70 (a)	70 (a)	70 (a)	70 (a)	70 (a)	30	30	30
2. Tug Boats - HP											
a. 1,500	each	-	-	-	-	-	-	-	-	-	-
b. 2,000	each	2	-	-	-	-	-	-	-	-	-
c. 3,000-4,000	each	17	-	-	-	-	-	-	5	5	5
d. 6,000	each	-	15	17	12	17	15	15	9	15	15
3. Pilot Launches											
a. 175 HP	each	4	-	-	-	-	-	-	2	2	2
b. 200-211 HP	each	3	-	-	-	-	-	-	2	2	2
c. 260 HP	each	6	-	-	-	-	-	-	4	4	4
d. 300 HP	each	26	9	9	9	9	9	9	18	18	18
e. 565 HP	each	2	1	1	1	1	1	1	2	2	2
4. Misc. Craft	each	8	3	3	3	3	3	3	6	6	6
5. Towing Locomotives											
a. 25,000 lb.Cap.	each	-	-	-	-	-	-	-	-	-	-
b. 70,000 lb.Cap./1 Wall	each	82	20	38	20	38	20	20	-	40	60
c. 70,000 lb.Cap./2 Wall	each	-	40	76	40	70	40	40	-	80	100
6. Communication Eqpt.	set	-	-	-	-	-	-	-	-	-	-
7. Video & Computer Eqpt.	set	-	-	-	-	-	-	-	-	-	-
8. Traffic Mgmt. Center	each	1	-	-	-	-	-	-	1	1	1
9. Pilot Lodging Facilities	each	2	-	-	-	-	-	-	2	2	2
10.Vehicles	each	25	5	5	5	5	5	5	25	25	25
11.Tide Gates	each	-	-	-	-	-	-	-	2	-	-
12.Tug Boat Tie-up	each	-	-	-	-	-	-	-	2	2	2
13.Beaching Areas	each	-	-	-	-	-	-	-	2	-	-
14.Turning Basins	each	-	-	-	-	-	-	-	2	-	-

NOTES:
(a) To be relocated under the alternative development programs.
(b) 166 range targets to be relocated and 40 new targets to be installed.
(c) 124 bank lights to be relocated and 50 new bank lights to be installed.

TABLE 10-2
SUMMARY OF ESTIMATED VALUES AND CAPITAL COSTS
(thousands of 1993 Dollars)

Alternatives	Additional Costs	
	One-Wall Operations	Two-Wall Operations
2	394,800	435,600
3	477,100	554,700
4	326,400	367,200
5	479,500	544,800
6	394,800	435,600
7	394,800	435,600
8	306,100	306,100
9	525,500	607,100
10	566,300	647,900

Note: See Table 10-3 for details.

TABLE 10-3
VALUES AND CAPITAL COSTS

Item	Cost/Unit	Relocation Cost/Unit	ESTIMATED COSTS – (Thousands of 1993 Dollars) Alternatives (Additional Costs) 2	3	4	5	6	7	8	9	10
1. Channel Navaids											
a. Range Lights	8,000	5,000	984	984	984	984	984	984	512	480	480
b. Bank Lights (1 lane)	10,000	2,000	–	–	–	–	–	–	5,300	6,940	6,940
c. Bank Lights (2 lanes)	25,000	2,000	1,498	1,498	1,498	1,498	1,498	1,498	1,300	500	500
d. Lighted Buoys	50,000	10,000	700	700	700	700	700	700	1,500	1,500	1,500
2. Tug Boats – HP											
a. 1,500	5,160,000	–	–	–	–	–	–	–	–	–	–
b. 2,000	6,140,000	–	–	–	–	–	–	–	–	–	–
c. 3,000–4,000	11,200,000	–	–	–	–	–	–	–	56,000	56,000	56,000
d. 6,000	19,000,000	–	285,000	323,000	228,000	325,000	285,000	285,000	171,000	285,000	285,000
3. Pilot Launches											
a. 175 HP	120,000	–	–	–	–	–	–	–	240	240	240
b. 200–211 HP	140,000	–	–	–	–	–	–	–	280	280	280
c. 260 HP	320,000	–	–	–	–	–	–	–	1,280	1,280	1,280
d. 300 HP	510,000	–	4,590	4,590	4,590	4,590	4,590	4,590	9,180	9,180	9,180
e. 565 HP	670,000	–	670	670	670	670	670	670	1,340	1,340	1,340
4. Misc. Craft	50,000	–	300	300	300	300	300	300	300	300	300
5. Towing Locomotives											
a. 70,000 lb.Cap/1 Wall	1,700,000	–	34,000	64,600	34,000	64,600	34,000	34,000	–	68,000	102,000
b. 70,000 lb.Cap/2 Wall	1,700,000	–	68,000	129,200	68,000	119,000	68,000	68,000	–	136,000	170,000
6. Communication Eqpt.	3,900,000	Exist.Facil.	1,000	1,000	1,000	1,000	1,000	1,000	4,000	4,000	4,000
7. Video & Computer Eqpt.	2,100,000	Exist.Facil.	200	200	200	200	200	200	2,500	2,500	2,500
8. Traffic Mgmt. Center	–	–	–	–	–	–	–	–	–	–	–
9. Pilot Lodging Facilities	–	–	–	–	–	–	–	–	–	–	–
10.Vehicles	15,000	–	75	75	75	75	75	75	375	375	375
11.Tide Gates	–	–	–	–	–	–	–	–	–	–	–
12.Tug Boat Tie-up	–	–	–	–	–	–	–	–	–	–	–
13.Beaching Areas	–	–	–	–	–	–	–	–	–	–	–
14.Turning Basins	–	–	–	–	–	–	–	–	–	–	–
Sub-Total – One Wall Operation			329,017	397,617	272,017	399,617	329,017	329,017	255,107	437,915	471,915
TOTAL One-Wall Operation -- Incl. 20% for Cont. & Eng.			394,820	477,140	326,420	479,540	394,820	394,820	306,128	525,498	566,298
TOTAL Two-Wall Operation -- Incl. 20% for Cont. & Eng.			435,620	554,660	367,220	544,820	435,620	435,620	306,128	607,098	647,898

The costs are estimated as of 1993, so that adjustments will have to be made for inflation in the financial analyses to be undertaken by others. In those analyses, schedules will also have to be established for replacement of the navigation aids and equipment in the Status Quo Program not only for the year 2020 by which time that program is planned to be completed, but also in the subsequent time frames, as in the case of the alternative scenarios, which are to be established as the life of the project.

ESTIMATED ANNUAL OPERATING AND MAINTENANCE COSTS

Summarized in Table 10-4 are the operating and maintenance costs estimated to be incurred annually in each of Alternatives 2 through 10, in addition to such annual costs for the Status Quo Program. Details of the estimates are given in Table 10-5.

The figures in Tables 10-4 and 10-5 are for three-shift per day operations as of the year 1993, and include an allowance of 15 percent for contingencies. As in the case of capital costs, the figures in Tables 10-4 and 10-5 will have to be adjusted for inflation in the financial analysis to be made by others. In addition to costs for maintenance of navigation aids, the estimates include payroll, fuel and power costs for operation and for maintenance of the tug boats, launches and towing locomotives required to assist ships in their navigation through the Canal. Also included are payroll costs for supervisory and other personnel engaged in navigation-related activities, as well as for traffic management personnel. An allowance has also been included for the cost of power and other utilities for operations at the traffic management center, but not for maintenance of the office building, nor for the maintenance of lock structures, tidal gates and other facilities.

Excluded from the estimates herein are amortization or depreciation and insurance costs for any equipment or facilities which it may be necessary to consider in the financial analyses to be made for the project.

TABLE 10-4
SUMMARY OF ESTIMATED ANNUAL OPERATING AND MAINTENANCE COSTS
(thousands of 1993 Dollars)

Alternatives	Costs Additional to Status Quo	
	One-Wall Operations	Two-Wall Operations
2	131,700	146,500
3	161,900	191,000
4	111,400	126,000
5	161,900	191,000
6	131,700	146,500
7	131,700	146,500
8*	114,300	114,300
9	187,300	219,300
10	203,300	235,400

Note: The total annual costs for each alternative (2 through 10) includes the cost of the status quo ($174,306,000) plus the additional cost listed for the alternative.

TABLE 10-5
NAVAIDS AND EQUIPMENT – ANNUAL OPERATING AND MAINTENANCE COSTS
(Thousands of 1993 Dollars)

Item	Costs Per Unit Per Year				ESTIMATED COSTS PER YEAR									
					Status Quo	Alternatives (Costs Additional to Status Quo)								
	Payroll	Fuel or Power	Maint.	Total		2	3	4	5	6	7	8	9	10
1. Channel Navaids														
a. Range Lights)														
b. Bank Lights-1 Lane)- Total All Aids for Item 1					672	181	181	180	180	181	180	660	656	656
c. Bank Lights-2 Lanes)														
d. Lighted Buoys)														
2. Tug Boats - HP (Incl. 20% spares)														
a. 1,500	500	608	842	1,950	-	-	-	-	-	-	-	-	-	-
b. 2,000	500	900	1,246	2,646	2,646	-	-	-	-	-	-	-	-	-
c. 3,000-4,000	500	1,575	2,182	4,257	66,144	-	-	-	-	-	-	19,210	19,210	19,210
d. 6,000	500	2,700	3,740	6,940	-	94,500	108,380	76,880	108,380	94,500	94,500	52,860	94,500	94,500
3. Pilot Launches														
a. 175 HP	126	79	109	314	1,256	-	-	-	-	-	-	628	628	628
b. 200-211 HP	126	90	125	341	1,023	-	-	-	-	-	-	682	682	682
c. 260 HP	126	117	162	405	1,560	-	-	-	-	-	-	7,620	1,620	1,620
d. 300 HP % spares)	126	135	187	448	10,865	3,771	3,771	3,771	3,771	3,771	3,771	7,542	7,542	7,542
e. 565 HP	126	255	352	733	1,466	733	733	733	733	733	733	1,466	1,466	1,466
f. Pilots					5,900	625	625	625	625	625	625	5,000	5,000	5,000
4. Misc.Craft l. 1 spare)	120	50	30	200	1,700	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020
5. Towing Locomotives (incl.15% spares)														
a. 25,000 lb.Cap.														
b. 70,000 lb.Cap/1 Wall	195	340	215	750	-	12,860	25,290	12,860	25,290	12,860	12,860	-	27,860	41,790
c. 70,000 lb.Cap/2-Wal	195	340	215	750	55,080	25,720	50,580	25,720	50,580	25,720	25,720	-	55,720	69,650
6. Communication Eqpt.	(10% of Equip. Costs)				5	100	100	100	100	100	100	400	400	400
7. Video & Computer Eqpt.	(15% of Equip. Costs)				8	30	30	30	30	30	30	375	375	375
8. Traffic Mgmt. Center					1,670	385	385	385	385	385	385	836	836	836
9. Pilot Lodging Facilities					100	-	-	-	-	-	-	100	100	100
10.Vehicles	18	0.5	0.5	19	475	95	95	95	95	95	95	475	475	475
11.General Supervision					1,000	200	200	200	200	200	200	500	500	500
Sub-Total - One Wall Operation						114,500	140,810	96,879	140,809	114,500	114,499	99,374	162,870	176,800
TOTAL One-Wall Annual Cost — Incl. 15% Cont.						131,675	161,932	111,411	161,930	131,675	131,674	114,280	187,301	203,320
TOTAL Two-Wall Annual Cost — Incl. 15% Cont.					174,306	146,464	191,015	126,200	191,014	146,464	146,463	114,280	219,339	235,359

Note: The total annual cost for each alternative includes the cost of the status quo plus the additional cost listed for the alternative.

NOTES REGARDING ESTIMATES

Navaids

- Estimates for range targets includes targets for three lanes at the Culebra Cut reflecting its use as both a single-lane and double-lane channel.

- Capital costs for navaids were based on information provided by Tidelands Signal Company, a manufacturer familiar with the existing aids in the Canal.

- Costs for maintaining navaids are based on gross annual costs provided by the PCC, which were then proportioned according to the lengths of waterways.

Tugboats and Launches

- The type, horsepower, purchase price and crew size of vessels are based on PCC-supplied data. Capital costs for tugboats are based on an average cost of $3,200 per horsepower.

- Payroll costs were derived from a PCC supplied annual cost for 569 persons, or an average of $23,800 per person annually. Higher costs were assumed for pilots, and lower for crews.

- Based on PCC supplied data, maintenance costs were estimated on the basis of $623 per horsepower. Costs for fuel, lubricants, etc. were based on a cost of $450 per horsepower annually.

Towing Locomotives

- Payroll costs were derived from the average salary costs indicated above. Based on PCC supplied data, it is estimated that the average annual cost for maintaining each locomotive is $215,000. Power costs were estimated at $344,000 per locomotive, annually.

Communications and Other

- Estimates were also made for the capital and operating costs of communications and traffic management equipment, supervisory costs and miscellaneous costs based on PCC furnished data.

CHAPTER 11

FRESH WATER CONSUMPTION - HIGH-RISE LOCKS

Presented herein are the results of analyses of fresh water consumption of selected high-rise and other cases, prepared at the request of CAS.

The water use factors for the various lock lifts and direction of ship travel (one-way or alternating in a given lock lane) used in the analysis are indicated below.

The term 'spill', below, is defined as the volume of water lost to the sea as a result of a ship's complete transit through a lock; spill is a function of H/n times the surface area of the lock (A), where H = 85 feet (25.9m) and n is a variable, as indicated below:

Single Lift Lock		(Pedro Miguel)	
one-way traffic	:	1 ship per spill - H/3	
alternating traffic	:	2 ships per spill - H/3	
Double Lift Lock		**(Existing Miraflores)**	**(New Atlantic and New Pacific)**
one-way traffic	:	1 ship per spill - H/3	1 ship per spill - H/2
alternating traffic	:	1 ship per spill - H/3	1 ship per spill - H.2
Triple Lift Lock		**(Existing Gatun)**	
one-way traffic	:	1 ship per spill - H/3	
alternating traffic	:	1 ship per spill - H/2	

Note that spills to the Pacific are governed by Miraflores locks.

The relationships derived from the above are:

Existing Miraflores

$$W = A \times H/3 \times L; \qquad A \times H/3 = 95{,}000 \text{ cubic meters}$$

Existing Gatun

$$W = A \times H/3\ (2L - C/2); \qquad A \times H/3 = 95{,}000 \text{ cubic meters}$$

New High-Rise Locks

$$W = A \times H/2 \times L$$

for 150,000 DWT: $A \times H/2 = 252{,}500$ cubic meters
200,000 DWT: $A \times H/2 = 299{,}100$ cubic meters

where,

C = no. of chamber operations per year
L = no. of lockages per year
W = annual water use, cubic meters

The Waterway Analysis Model was run for the required cases using the WEFA forecasts of ship transits for year 2020 and 2060 to obtain the number of annual chamber operations and lockages. The model assumed operations that would optimize capacity, rather than minimize water consumption. The results are indicated in Table 11-1.

In summary, the estimated total volumes of fresh water consumed as a result of lockages (in millions of cubic meters (M.c.m.)) for alternative Cases 2, 4 and 8 in the years 2020 and 2060 are as follows:

TOTAL FRESH WATER USE (M.c.m.)

	Case	Year 2020	Year 2060
2	High-Rise Locks (150,000 DWT)	6,381	8,029
4	High-Rise Locks (200,000 DWT)	7,214	8,965
8	Status Quo Route (Used with Sea-Level Canal, Tide Gates)	1,731	2,033

TABLE 11-1
FRESH WATER CONSUMPTION - HIGH-RISE LOCKS

	Gatun		Miraflores		New Atlantic		New Pacific	
	2020	2060	2020	2060	2020	2060	2020	2060
CASE 2								
A x H/3, c.m.	95,000		95,000					
A x H/2, c.m.					252,500		252,500	
Lockages	9,692	12,646	8,602	12,414	8,246	10,458	9,204	10,694
Chamber Operations	14,482	18,944						
Water Use, M.c.m.	1,156	1,506	819	1,182	2,082	2,641	2,324	2,700
CASE 4								
A x H/3, c.m.	95,000		95,000					
A x H/2, c.m.					299,100		299,100	
Lockages	9,540	12,320	8,400	12,020	8,350	10,460	9,288	10,784
Chamber Operations	14,230	18,464						
Water Use, M.c.m.	1,139	1,467	800	1,144	2,497	3,129	2,778	3,225
CASE 8								
A x H/3, c.m.	95,000		95,000					
Lockages	8,134	9,530	8,148	9,614				
Chamber Operations	12,464	14,634						
Water Use, M.c.m.	955	1,118	776	915				

c.m. = cubic meters
M.c.m. = millions of cubic meters

APPENDIX A

TRANSIT AND LOCKAGE DATA

TABLE A-1
SAMPLE VESSEL TRANSIT TIMES
(By Vessel Beam)

Under 60

Name of ship	V/L L	Dim B	Leave Balboa	Tn1	Miraflores Locks Arrive	Miraflores Locks Leave	Miraflores Locks Tn2	Miraflores Lake Tn3	Pedro Miguel Locks Loco Arr. Time	Pedro Miguel Locks V/L Arrived	Pedro Miguel Locks V/L Entered	Pedro Miguel Locks V/L Cleared	Pedro Miguel Locks Tn4(a)	Pedro Miguel Locks Tn4(b)	Pedro Miguel Locks Tn4	Pedro Miguel Locks Late Loco arr	Pass Gamboa	Gaillard Cut Tn5	Gatun Lake Tn6	Gatun Locks Arrive	Gatun Locks Leave	Gatun Locks Tn7	Arrive Cristobal	Tn8
Nancy G	317	52		2:47	2:47	3:29	0:42	0:18	3:40	3:47	3:55	4:12	0:08	0:17	0:25	0	5:09	0:57	5:28	10:37	11:44	1:07		-11:44
Las Perlas	404	54		21:31	21:31	22:14	0:43	1:07	23:53	23:21	0:28	1:02	1:07	0:34	1:41	1	1:52	0:50	1:48	3:40	4:50	1:10		-4:50
Kathleen Pearcy	338	50		2:42	2:42	3:26	0:44	0:22	3:55	3:48	4:00	4:27	0:12	0:27	0:39	1	8:12	3:45	2:32	10:44	11:52	1:08		-11:52
Emanuel B	473	59		15:14	15:14	16:03	0:49	0:13	16:10	16:16	16:22	16:52	0:06	0:30	0:36	0	18:07	1:15	4:36	22:43	23:44	1:01		-23:44
Lockwood	438	46		17:12	17:12	17:55	0:43	0:20	18:10	18:15	18:22	18:47	0:07	0:25	0:32	0	19:51	1:04	4:23	0:13	1:14	1:01		-1:14
Jomaas	396	60		17:55	17:55	18:44	0:49	0:16	18:52	19:00	19:06	19:30	0:06	0:24	0:30	0	20:26	0:56	2:19	22:45	23:59	1:14		-23:59
Janne Terkol	273	44		20:15	20:15	21:45	1:30	0:08	21:51	21:53	21:58	22:18	0:05	0:20	0:25	0	22:57	0:39	3:50	2:47	4:05	1:18		-4:05

Name of ship	V/L L	Dim B	Leave Cristobal	Ts1	Gatun Locks Arrive	Gatun Locks Leave	Gatun Locks Ts2	Gatun Lake Ts3	Pass Gamboa	Gaillard Cut Ts4	Pedro Miguel Locks Loco Arr. Time	Pedro Miguel Locks V/L Arrived	Pedro Miguel Locks V/L Entered	Pedro Miguel Locks V/L Cleared	Pedro Miguel Locks Ts5 (a)	Pedro Miguel Locks Ts5 (b)	Pedro Miguel Locks Ts5	Pedro Miguel Locks Late Loco arr	Miraflores Lake Ts6	Miraflores Locks Arrive	Miraflores Locks Leave	Miraflores Locks Ts7	Arrive Balboa	Ts8
Carirubana	220	38		17:17	17:17	18:16	0:59	1:53	20:09	0:59	21:31	21:08	21:35	22:01	0:27	0:26	0:53	1	0:13	22:14	22:56	0:42		-22:56
Mini Lama	214	50		20:36	20:36	21:43	1:07	2:53	0:36	1:12	1:46	1:48	1:56	2:18	0:08	0:22	0:30	0	0:14	2:32	3:07	0:35		-3:07
Asahi Maru	354	53		3:37	3:37	4:40	1:03	13:12	17:52	1:09	18:43	19:01	19:09	19:45	0:08	0:36	0:44	0	0:20	20:05	20:52	0:47		-20:52
Aleta Azul	229	42		3:22	3:22	4:38	1:16	13:31	18:09	1:00	19:57	19:09	20:13	20:45	1:04	0:32	1:36	1	0:14	20:59	21:36	0:37		-21:36
C.S.Alert	417	54		19:30	19:30	20:39	1:09	1:48	22:27	2:10	0:36	0:37	0:51	1:13	0:14	0:22	0:36	0	0:22	1:35	2:23	0:48		-2:23
PCG Chame II	141	35		0:00			0:00	10:50	10:50	0:59	11:49	11:49	11:53	12:09	0:04	0:16	0:20	0	0:08	12:17	12:49	0:32		-12:49
Dirk Jacob	560	35		4:26	4:26	6:04	1:38	5:50	11:54	0:57	12:39	12:51	12:57	13:41	0:06	0:44	0:50	0	0:18	13:59	14:43	0:44		-14:43

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Name of ship	V/L L	Dim B	Leave Balboa	Tn1	Miraflores Locks Arrive	Miraflores Locks Leave	Miraflores Locks Tn2	Miraflores Lake Tn3	Pedro Miguel Locks Loco Arr Time	Pedro Miguel Locks V/L Arrived	Pedro Miguel Locks V/L Entered	Pedro Miguel Locks V/L Cleared	Pedro Miguel Locks Tn4(a)	Pedro Miguel Locks Tn4(b)	Pedro Miguel Locks Tn4	Pedro Miguel Locks Late Loco arr	Pass Gamboa	Gaillard Cut Tn5	Gatun Lake Tn6	Gatun Locks Arrive	Gatun Locks Leave	Gatun Locks Tn7	Arrive Cristobal	Tn8
Kavo Alexandros	567	64		3:15	3:15	4:04	0:49	0:23	4:22	4:27	4:36	5:02	0:09	0:26	0:35	0	7:12	2:10	4:22	11:34	12:40	1:06		-12:40
Mistrau	465	64		18:23	18:23	19:05	0:42	0:14	19:06	19:19	19:25	20:01	0:06	0:36	0:42	0	20:49	0:48	1:39	22:28	23:31	1:03		-23:31
Panandros	470	65		21:55	21:55	22:42	0:47	0:20	22:25	23:02	23:10	23:46	0:08	0:36	0:44	0	0:50	1:04	2:45	3:35	4:38	1:03		-4:38
Samoan Reefer	540	68		22:53	22:53	23:45	0:52	0:16	23:54	0:01	0:13	0:52	0:12	0:39	0:51	0	8:16	7:24	2:49	11:05	12:53	1:48		-12:53
African Princess	495	69		9:00	9:00	9:44	0:44	0:35	10:24	10:19	10:33	10:58	0:14	0:25	0:39	1	11:53	0:55	3:00	14:53	16:36	1:43		-16:36
Apple Blossom	500	63		16:17	16:17	16:59	0:42	0:16	17:09	17:15	17:21	17:47	0:06	0:26	0:32	0	18:32	0:45	4:52	23:24	0:30	1:06		-0:30
Isla Duna	429	62		20:00	20:00	20:51	0:51	0:40	21:17	21:31	21:37	22:14	0:06	0:37	0:43	0	23:13	0:59	3:24	2:37	4:02	1:25		-4:02

Name of ship	V/L L	Dim B	Leave Cristobal	Ts1	Gatun Locks Arrive	Gatun Locks Leave	Gatun Locks Ts2	Gatun Lake Ts3	Pass Gamboa	Gaillard Cut Ts4	Pedro Miguel Locks Loco Arr Time	Pedro Miguel Locks V/L Arrived	Pedro Miguel Locks V/L Entered	Pedro Miguel Locks V/L Cleared	Pedro Miguel Locks Ts5 (a)	Pedro Miguel Locks Ts5 (b)	Pedro Miguel Locks Ts5	Pedro Miguel Locks Late Loco arr	Miraflores Lake Ts6	Miraflores Locks Arrive	Miraflores Locks Leave	Miraflores Locks Ts7	Arrive Balboa	Ts8
Bonita	543	68		18:19	18:19	19:32	1:13	1:27	20:59	1:17	22:30	22:16	22:38	23:08	0:22	0:30	0:52	1	0:17	23:25	0:11	0:46		-0:11
Min Jang	491	69		19:43	19:43	20:57	1:14	1:38	22:35	1:26	0:01	0:01	0:11	0:34	0:10	0:23	0:33	0	0:18	0:52	1:37	0:45		-1:37
Manolis	501	66		20:26	20:26	22:35	2:09	1:45	0:20	1:01	1:22	1:21	1:29	1:52	0:08	0:23	0:31	1	0:12	2:04	2:48	0:44		-2:48

Source: Panama Canal Commission

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Name of ship	V/L L	Dim B	Leave Balboa	Tn1	Miraflores Locks Arrive	Leave	Tn2	Miraflores Lake Tn3	Pedro Miguel Locks Loco Arr. Time	V/L Arrived	V/L Entered	V/L Cleared	Tn4(a)	Tn4(b)	Tn4	Late Loco arr	Pass Gamboa	Gaillard Cut Tn5	Gatun Lake Tn6	Gatun Locks Arrive	Leave	Tn7	Arrive Cristobal	Tn8
Ciudad de Manta	528	75		8:33	8:33	9:15	0:42	0:17	9:41	9:32	9:47	10:23	0:15	0:36	0:51	1	11:14	0:51	10:43	21:57	23:03	1:06		-23:03
Standwear	525	75		21:07	21:07	21:57	0:50	0:18	22:55	22:15	23:07	23:43	0:52	0:36	1:28	1	0:33	0:50	1:52	2:25	3:32	1:07		-3:32
Avelona Star	511	70		20:33	20:33	21:21	0:48	0:12	21:25	21:33	21:40	22:15	0:07	0:35	0:42	0	22:45	0:30	1:36	0:21	1:50	1:29		-1:50
Cuenca	500	74		9:50	9:50	10:38	0:48	0:31	11:07	11:09	11:19	11:47	0:10	0:28	0:38	0	12:37	0:50	3:09	15:46	17:14	1:28		-17:14
Trinton Reefer	472	70		10:00	10:00	10:45	0:45	0:29	11:12	11:14	11:29	12:05	0:15	0:36	0:51	0	12:50	0:45	4:12	17:02	18:13	1:11		-18:13
Ayogalusena	567	74		10:45	10:45	11:35	0:50	0:16	12:00	11:51	12:07	12:36	0:16	0:29	0:45	1	18:02	5:26	3:59	22:01	23:11	1:10		-23:11
Van K	648	79		19:10	19:10	20:04	0:54	0:24	19:57	20:28	20:38	21:12	0:10	0:34	0:44	0	22:45	1:33	4:16	1:28	2:53	1:25		-2:53
Chiquita Baracoa	557	78		21:29	21:29	22:11	0:42	0:28	22:40	22:39	23:03	23:37	0:24	0:34	0:58	1	0:24	0:47	1:47	2:11	4:10	1:59		-4:10
Jollity	539	75		22:12	22:12	23:14	1:02	0:37	23:50	23:51	0:04	0:42	0:13	0:38	0:51	0	1:38	0:56	2:06	3:44	4:50	1:06		-4:50
Akti	593	75		2:04	2:04	2:48	0:44	0:12	2:35	3:00	3:06	3:30	0:06	0:24	0:30	0	4:15	0:45	19:36	23:51	1:17	1:26		-1:17
Omisalj	728	75		3:39	3:39	4:28	0:49	0:16	3:20	4:44	4:55	5:19	0:11	0:24	0:35	0	7:42	2:23	12:28	20:10	21:21	1:11		-21:21
Sea Empire	575	76		22:06	22:06	22:53	0:47	0:24	23:29	23:17	23:46	0:23	0:29	0:37	1:06	1	1:20	0:57	2:56	4:16	5:27	1:11		-5:27
Vitoria	563	79		3:33	3:33	4:24	0:51	0:29	4:30	4:53	5:08	5:35	0:15	0:27	0:42	0	8:29	2:54	14:25	22:54	0:02	1:08		-0:02
Irini	518	75		4:36	4:36	5:34	0:58	0:23	5:55	5:57	5:59	6:24	0:02	0:25	0:27	0	8:39	2:15	-6:04	2:35	3:39	1:04		-3:39
Golden Polydinamo	565	75		20:18	20:18	21:16	0:58	0:20	21:07	21:36	21:47	22:11	0:11	0:24	0:35	0	23:21	1:10	2:24	1:45	2:50	1:05		-2:50
Ciudad De Ra...	518	75		20:33	20:33	21:21	0:48	0:56	22:19	22:17	22:27	22:49	0:10	0:22	0:32	1	23:37	0:48	2:25	2:02	4:15	2:13		-4:15
Sea Empress	575	76		19:19	19:19	20:06	0:47	0:14	20:14	20:20	20:28	20:55	0:08	0:27	0:35	0	21:59	1:04	2:50	0:49	2:13	1:24		-2:13

Name of ship	V/L L	Dim B	Leave Cristobal	Ts1	Gatun Locks Arrive	Leave	Ts2	Gatun Lake Ts3	Pass Gamboa	Gaillard Cut Ts4	Pedro Miguel Locks Loco Arr. Time	V/L Arrived	V/L Entered	V/L Cleared	Ts5(a0	Ts5(b)	Ts5	Late Loco arr.	Miraflores Lake Ts6	Miraflores Locks Arrive	Leave	Ts7	Arrive Balboa	Ts8
Rong Chen	484	75		4:15	4:15	5:17	1:02	10:51	16:08	1:03	16:56	17:11	17:17	17:49	0:06	0:32	0:38	0	1:29	19:18	20:01	0:43		-20:01
Asia Rainbow	507	75		4:56	4:56	5:55	0:59	8:31	14:26	1:26	15:54	15:52	16:10	16:47	0:18	0:37	0:55	1	0:17	17:04	17:43	0:39		-17:43
Frio Atlantic	478	70		5:46	5:46	6:48	1:02	4:48	11:36	1:00	12:20	12:36	12:44	13:18	0:08	0:34	0:42	0	0:16	13:34	14:14	0:40		-14:14
Tineke	508	74		16:53	16:53	17:55	1:02	2:05	20:00	1:12	21:10	21:12	21:20	21:45	0:08	0:25	0:33	0	0:17	22:02	22:49	0:47		-22:49
Rio Chama	579	75		19:33	19:33	20:53	1:20	2:13	23:06	1:16	0:17	0:22	0:33	1:03	0:11	0:30	0:41	0	0:21	1:24	2:14	0:50		-2:14
Cape Bon	540	76		19:51	19:51	21:39	1:48	1:35	23:14	1:25	1:13	0:39	1:16	1:38	0:37	0:22	0:59	1	0:20	1:58	2:44	0:46		-2:44
Caurica	556	74		20:18	20:18	21:43	1:25	1:58	23:41	1:19	0:20	1:00	1:29	1:51	0:29	0:22	0:51	0	0:21	2:12	2:57	0:45		-2:57
Pocahontas	496	70		19:49	19:49	20:55	1:06	2:48	23:43	0:42	0:13	0:25	0:37	0:56	0:12	0:19	0:31	0	0:07	1:03	1:51	0:48		-1:51
Santa Clara I	478	70		5:12	5:12	6:19	1:07	5:24	11:43	1:00	12:22	12:43	12:49	13:12	0:06	0:23	0:29	0	0:19	13:31	14:13	0:42		-14:13
Bled	648	79		18:34	18:34	19:58	1:24	1:54	21:52	1:04	23:02	22:56	23:13	23:42	0:17	0:29	0:46	1	0:30	0:12	1:03	0:51		-1:03
Golfo De Guacan	534	74		16:48	16:48	17:53	1:05	2:34	20:27	1:12	21:39	21:39	21:47	22:08	0:08	0:21	0:29	0	0:12	22:20	23:02	0:42		-23:02
Socrates	584	75		20:04	20:04	21:20	1:16	1:59	23:19	1:17	0:28	0:38	0:47	1:15	0:09	0:28	0:37	0	0:21	1:36	2:25	0:49		-2:25
Indian Ocean	495	72		18:14	18:14	19:16	1:02	1:10	20:26	0:59	21:10	21:25	21:32	21:58	0:07	0:26	0:33	0	0:19	22:17	23:02	0:45		-23:02
Spring Panda	494	78		18:00	18:00	19:03	1:03	1:37	20:40	1:01	22:08	21:41	22:13	22:37	0:32	0:24	0:56	1	0:15	22:52	23:36	0:44		-23:36
Sea Dragon	575	76		19:19	19:19	20:23	1:04	2:06	22:29	1:18	23:38	23:47	23:55	0:22	0:08	0:27	0:35	0	0:21	0:43	1:28	0:45		-1:28

TABLE A-1 (cont'd)

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Name of ship	V/L L	Dim B	Leave Balboa	Tn1	Miraflores Locks Arrive	Leave	Tn2	Miraflores Lake Tn3	Pedro Miguel Locks Loco Arr. Time	V/L Arrived	V/L Entered	V/L Cleared	Tn4(a)	Tn4(b)	Tn4	Late Loco arr	Pass Gamboa	Gaillard Cut Tn5	Gatun Lake Tn6	Gatun Locks Arrive	Leave	Tn7	Arrive Cristobal	Tn8
Cielo Di Amalei	601	87		9:55	9:55	10:51	0:56	0:28	11:02	11:19	11:30	12:12	0:11	0:42	0:53	0	17:11	4:59	3:32	20:43	22:09	1:26		-22:09
Bergen Falcon	641	83		4:08	4:08	5:03	0:55	0:42	5:13	5:45	5:58	6:50	0:13	0:52	1:05	0	7:48	0:58	-5:16	1:32	2:40	1:08		-2:40
Isabel Barreta	562	82		6:43	6:43	7:41	0:58	0:58	9:05	8:39	9:13	9:41	0:34	0:28	1:02	1	10:46	1:05	3:49	14:35	16:33	1:58		-16:33
Royal Viking Sky	674	82		7:56	7:56	8:51	0:55	1:03	9:56	9:54	10:04	11:19	0:10	1:15	1:25	1	11:45	0:26	-9:53	1:52	3:15	1:23		-3:15
Great Glen	559	80		20:20	20:20	21:47	1:27	0:34	22:30	22:21	22:46	23:19	0:25	0:33	0:58	1	0:11	0:52	2:17	2:28	4:35	2:07		-4:35
Ocean Cosmos	523	85		18:52	18:52	19:43	0:51	0:31	20:06	20:14	20:22	20:48	0:08	0:26	0:34	0	21:43	0:55	2:35	0:18	1:27	1:09		-1:27
Flag Williams	619	83		19:55	19:55	20:51	0:56	0:19	21:03	21:10	21:17	21:41	0:07	0:24	0:31	0	22:38	0:57	2:27	1:05	2:48	1:43		-2:48
Delena 1	574	83		8:23	8:23	9:22	0:59	0:12		9:34	9:42	10:10	0:08	0:28	0:36	0	11:15	1:05	10:47	22:02	23:03	1:01		-23:03
Envoyager	500	87		17:59	17:59	19:17	1:18	0:17	19:18	19:34	19:41	20:08	0:07	0:27	0:34	0	20:57	0:49	3:12	0:09	1:26	1:17		-1:26

Name of ship	V/L L	Dim B	Leave Cristobal	Ts1	Gatun Locks Arrive	Leave	Ts2	Gatun lake Ts3	Pass Gamboa	Gaillard Cut Ts4	Pedro Miguel Locks Loco Arr. Time	V/L Arrived	V/L Entered	V/L Cleared	Ts5 (a)	Ts5 (b)	Ts5	Late Loco arr	Miraflores Lake Ts6	Miraflores Locks Arrive	Leave	Ts7	Arrive Balboa	Ts8
Sonia	562	84		2:51	2:51	4:04	1:13	11:27	15:31	1:30	17:00	17:01	17:11	18:41	0:10	1:30	1:40	0	0:47	19:28	20:54	1:26		-20:54
An Hai	635	86		3:29	3:29	4:40	1:11	6:50	11:30	0:52	12:05	12:22	12:29	13:01	0:07	0:32	0:39	0	0:13	13:14	13:56	0:42		-13:56
Silver Sorrel	527	82		17:47	17:47	19:14	1:27	1:55	21:09	1:14	22:12	22:23	22:31	23:04	0:08	0:33	0:41	0	0:19	23:23	0:26	1:03		-0:26
Bow Princess	560	85		6:09	6:09	7:22	1:13	4:19	11:41	1:10	12:41	12:51	13:00	13:36	0:09	0:36	0:45	0	0:19	13:55	14:43	0:48		-14:43
Stolt Excellence	579	88		8:57	8:57	10:25	1:28	2:24	12:49	1:38	14:41	14:27	15:03	15:44	0:36	0:41	1:17	1	0:19	16:03	16:51	0:48		-16:51
Nedlloyd Barcelona	568	89		5:11	5:11	6:17	1:06	5:54	12:11	1:07	12:47	13:18	13:25	13:57	0:07	0:32	0:39	0	0:22	14:19	15:01	0:42		-15:01
Pioneer Leader	654	83		4:54	4:54	6:05	1:11	3:56	10:01	0:53	10:41	10:54	11:08	11:35	0:14	0:27	0:41	0	0:16	11:51	12:40	0:49		-12:40
Mar Bonita	573	88		16:31	16:31	17:34	1:03	1:49	19:23	1:35	20:53	20:58	21:05	21:32	0:07	0:27	0:34	0	0:18	21:50	22:44	0:54		-22:44
Merchant Prince	579	83		18:10	18:10	19:17	1:07	2:15	21:32	1:03	22:24	22:35	22:42	23:09	0:07	0:27	0:34	0	0:14	23:23	0:13	0:50		-0:13
Winter Star	555	84		5:03	5:03	6:15	1:12	5:49	12:04	0:45	12:39	12:49	12:57	13:35	0:08	0:38	0:46	0	0:13	13:48	14:33	0:45		-14:33

TABLE A-1 (cont'd)

90 - 99

Name of ship	V/L L	Dim B	Leave Balboa	Tn1	Miraflores Locks Arrive	Leave	Tn2	Miraflores Lake Tn3	Pedro Miguel Locks Loco Arr	Time	V/L Arrived	V/L Entered	V/L Cleared	Tn4(a)	Tn4(b)	Tn4	Late Loco arr	Gaillard Cut Pass Gamboa	Tn5	Gatun Lake Tn6	Gatun Locks Arrive	Leave	Tn7	Arrive Cristobal	Tn8
Act 6	712	95		3:49	3:49	4:55	1:06	0:33	5:31		5:28	5:40	6:14	0:12	0:34	0:46	1	7:25	1:11	8:16	15:41	17:05	1:24		-17:05
Trinta	597	95		4:15	4:15	5:14	0:59	0:31	6:29		5:45	6:36	7:07	0:51	0:31	1:22	1	8:18	1:11	3:34	11:52	13:15	1:23		-13:15
Fuji Ace	654	98		6:45	6:45	8:17	1:32	0:22	8:50		8:39	8:55	9:31	0:16	0:36	0:52	1	10:24	0:53	5:29	15:53	17:23	1:30		-17:23
New Ruby	616	91		7:38	7:38	8:42	1:04	0:43	9:24		9:25	9:43	10:27	0:18	0:44	1:02	0	11:25	0:58	11:01	22:26	23:45	1:19		-23:45
Hannover	599	97		8:26	8:26	9:26	1:00	0:25	9:50		9:51	10:01	10:32	0:10	0:31	0:41	0	11:27	0:55	3:52	15:19	16:40	1:21		-16:40
CGM Provence	581	90		9:36	9:36	10:30	0:54	0:14	10:43		10:44	10:52	11:20	0:08	0:28	0:36	0	12:07	0:47	2:52	14:59	16:42	1:43		-16:42
Skautroll	610	93		3:18	3:18	4:18	1:00	0:27	4:36		4:45	4:57	5:32	0:12	0:35	0:47	0	8:23	2:51	2:26	10:49	12:11	1:22		-12:11
Sinbad	606	99		3:39	3:39	4:35	0:56	1:09	5:52		5:44	5:53	8:12	0:09	2:19	2:28	1	9:01	0:49	2:26	11:27	13:24	1:57		-13:24
Samuel H Armacos	587	99		8:43	8:43	9:40	0:57	0:27	10:14		10:07	10:22	11:01	0:15	0:39	0:54	1	12:01	1:00	2:29	14:30	16:04	1:34		-16:04
Ljubljana	600	90		20:17	20:17	21:15	0:58	0:22	21:03		21:37	21:46	22:32	0:09	0:46	0:55	0	23:42	1:10	2:24	2:06	3:29	1:23		-3:29
Fantasy L	636	93		2:37	2:37	3:22	0:45	0:13	3:10		3:35	3:41	4:15	0:06	0:34	0:40	0	6:50	2:35	7:34	14:24	15:53	1:29		-15:53
Golden Farmer	616	91		5:50	5:50	6:51	1:01	0:28	8:04		7:19	8:12	8:45	0:53	0:33	1:26	1	9:49	1:04	2:57	12:46	15:20	2:34		-15:20
Rotterdam	748	94		7:30	7:30	8:19	0:49	0:16	8:36		8:35	8:44	9:10	0:09	0:26	0:35	1	10:05	0:55	3:17	13:22	14:31	1:09		-14:31
Imithea	606	90		8:40	8:40	9:29	0:49	0:17	9:32		9:46	9:54	10:21	0:08	0:27	0:35	0	11:19	0:58	3:31	14:50	16:07	1:17		-16:07
Omi Willamette	660	90		19:08	19:08	20:13	1:05	0:12	20:30		20:25	20:35	21:23	0:10	0:48	0:58	1	22:17	0:54	2:09	0:26	1:58	1:32		-1:58

Name of ship	V/L L	Dim B	Leave Cristobal	Ts1	Gatun Locks Arrive	Leave	Ts2	Gatun Lake Ts3	Gaillard Cut Pass Gamboa	Ts4	Pedro Miguel Locks Loco Arr	Time	V/L Arrived	V/L Entered	V/L Cleared	Ts5 (a)	Ts5 (b)	Ts5	Late Loco arr	Miraflores Lake Ts6	Miraflores Locks Arrive	Leave	Ts7	Arrive Balboa	Ts8
Youssoufia	615	93		6:32	6:32	8:28	1:56	4:04	12:32	1:30	13:49		14:02	14:14	15:00	0:12	0:46	0:58	0	0:21	15:21	16:11	0:50		-16:11
Kelvin Resource	619	93		6:45	6:45	8:19	1:34	7:31	15:50	1:21	17:03		17:11	17:18	18:06	0:07	0:48	0:55	0	0:30	18:36	19:48	1:12		-19:48
Vasiliy Koval	599	98		8:51	8:51	10:40	1:49	3:21	14:01	1:33	15:22		15:34	15:41	16:45	0:07	1:04	1:11	0	0:33	17:18	18:41	1:23		-18:41
An Ping 3	639	93		6:34	6:34	8:04	1:30	4:02	12:06	1:16	13:20		13:22	13:33	14:14	0:11	0:41	0:52	0	0:22	14:36	15:31	0:55		-15:31
Jian He	646	97		5:39	5:39	7:26	1:47	8:27	15:53	1:24	18:08		17:17	18:13	18:53	0:56	0:40	1:36	1	1:17	20:10	21:54	1:44		-21:54
Golden Topaz	621	98		11:40	11:40	13:13	1:33	1:50	15:03	1:15	16:04		16:18	16:33	17:09	0:15	0:36	0:51	0	0:28	17:37	18:56	1:19		-18:56
Star Livamo	612	98		10:36	10:36	11:57	1:21	2:36	14:33	1:15	15:34		15:48	15:57	16:44	0:09	0:47	0:56	0	0:37	17:21	19:24	2:03		-19:24

TABLE A-1 (cont'd)

100 - Over

Name of ship	V/L L	Dim B	Leave Balboa	Tn1	Miraflores Locks Arrive	Leave	Tn2	Miraflores Lake Tn3	Pedro Miguel Locks Loco Arr Time	V/L Arrived	V/L Entered	V/L Cleared	Tn4(a)	Tn4(b)	Tn4	Late Loco arr	Pass Gamboa	Gaillard Cut Tn5	Gatun Lake Tn6	Gatun Locks Arrive	Leave	Tn7	Arrive Cristobal	Tn8
OOCL Fortune	790	105		4:57	4:57	6:03	1:06	0:35	7:18	6:38	7:22	7:49	0:44	0:27	1:11	1	8:44	0:55	3:23	12:07	14:12	2:05		-14:12
Pobeda	796	105		5:26	5:26	6:51	1:25	0:31	8:04	7:22	8:07	9:14	0:45	1:07	1:52	1	10:11	0:57	2:25	12:36	15:08	2:32		-15:08
Marchen Maresk	964	105		6:14	6:14	7:27	1:13	0:31	7:59	7:58	8:07	8:41	0:09	0:34	0:43	1	9:40	0:59	4:41	14:21	15:45	1:24		-15:45
Svet Vlaho	619	100		2:59	2:59	3:52	0:53	0:15	3:50	4:07	4:14	4:41	0:07	0:27	0:34	0	6:40	1:59	3:56	10:36	11:58	1:22		-11:58
Eurasian Beauty	603	100		3:58	3:58	4:56	0:58	0:17	5:07	5:13	5:20	5:57	0:07	0:37	0:44	0	6:54	0:57	4:44	11:38	12:51	1:13		-12:51
Continental Wing	623	105		4:14	4:14	5:14	1:00	0:52	6:02	6:06	6:16	6:45	0:10	0:29	0:39	0	7:38	0:53	4:11	11:49	13:31	1:42		-13:31
Choyang Park	787	105		4:56	4:56	6:03	1:07	0:35	6:55	6:38	6:59	7:27	0:21	0:28	0:49	1	8:29	1:02	3:28	11:57	13:30	1:33		-13:30
White Sea	688	105		5:54	5:54	7:15	1:21	0:21	7:34	7:36	7:50	8:34	0:14	0:44	0:58	0	9:39	1:05	2:42	12:21	14:44	2:23		-14:44
Regulus	946	105		6:47	6:47	8:09	1:22	0:29	8:29	8:38	8:53	9:46	0:15	0:53	1:08	0	11:09	1:23	2:33	13:42	15:19	1:37		-15:19
Akrop	734	105		7:24	7:24	8:26	1:02	0:25	8:46	8:51	9:08	9:38	0:17	0:30	0:47	0	10:32	0:54	2:40	13:12	15:27	2:15		-15:27
Lei Zhou Hai	733	105		6:00	6:00	7:06	1:06	0:37	7:40	7:43	7:53	8:42	0:10	0:49	0:59	0	9:53	1:11	2:47	12:40	14:32	1:52		-14:32
Ming Prominence	884	105		6:23	6:23	7:39	1:16	0:44	8:24	8:23	8:35	9:10	0:12	0:35	0:47	1	10:19	1:09	3:00	13:19	15:08	1:49		-15:08
Ever Gentry	757	105		4:48	4:48	5:56	1:08	0:23	6:26	6:19	6:29	7:14	0:10	0:45	0:55	1	8:29	1:15	3:35	12:04	13:45	1:41		-13:45
Nedlloyd Clement	688	105		7:16	7:16	8:16	1:00	0:46	9:00	9:02	9:14	9:56	0:12	0:42	0:54	0	10:54	0:58	2:40	13:34	15:18	1:44		-15:18
Limbhazi	630	101		4:53	4:53	5:55	1:02	0:21	7:02	6:16	7:05	7:39	0:49	0:34	1:23	1	8:33	0:54	3:30	12:03	13:42	1:39		-13:42
Nile River	771	105		5:17	5:17	6:44	1:27	0:33	7:48	7:17	7:57	8:49	0:40	0:52	1:32	1	9:54	1:05	3:26	13:20	15:02	1:42		-15:02
Alligator Liberty	807	105		6:10	6:10	7:10	1:00	0:46	8:11	7:56	8:21	9:08	0:25	0:47	1:12	1	10:17	1:09	3:29	13:46	15:25	1:39		-15:25
Maritime Pearl	590	100		3:18	3:18	4:08	0:50	0:32	4:58	4:40	5:02	5:29	0:22	0:27	0:49	1	7:12	1:43	15:27	22:39	23:51	1:12		-23:51
Jubilant	705	105		4:22	4:22	5:30	1:08	0:20	5:42	5:50	6:00	6:29	0:10	0:29	0:39	0	7:22	0:53	4:01	11:23	12:45	1:22		-12:45
Glory Pegasus	578	105		4:43	4:43	5:41	0:58	0:57	6:39	6:38	6:48	7:18	0:10	0:30	0:40	1	8:07	0:49	4:20	12:27	13:53	1:26		-13:53
Beacon	738	105		5:30	5:30	6:36	1:06	0:21	7:28	6:57	7:31	7:55	0:34	0:24	0:58	1	8:43	0:48	4:02	12:45	14:19	1:34		-14:19
Yick Fat	622	102		6:33	6:33	7:40	1:07	0:17	8:04	7:57	8:09	8:35	0:12	0:26	0:38	1	9:27	0:52	2:04	1:56	3:36	1:40		-3:36
Eagle	648	105		4:49	4:49	5:57	1:08	0:22	6:37	6:19	6:42	7:06	0:23	0:24	0:47	1	8:54	1:48	7:45	16:39	17:54	1:15		-17:54
Century Highway 1	611	104		6:22	6:22	7:18	0:56	0:19	7:28	7:37	7:43	8:12	0:06	0:29	0:35	0	9:08	0:56	6:16	15:24	16:35	1:11		-16:35
Hua Rong Shan	639	104		7:04	7:04	8:16	1:12	0:19	8:10	8:35	8:44	9:28	0:09	0:44	0:53	0	10:45	1:17	2:51	13:36	15:11	1:35		-15:11

Name of ship	V/L L	Dim B	Leave Cristobal	Ts1	Gatun Locks Arrive	Leave	Ts2	Gatun Lake Ts3	Pass Gamboa	Gaillard Cut Ts4	Pedro Miguel Locks Loco Arr Time	V/L Arrived	V/L Entered	V/L Cleared	Ts5 (a)	Ts5 (b)	Ts5	Late Loco arr	Miraflores Lake Ts6	Miraflores Locks Arrive	Leave	Ts7	Arrive Balboa	Ts8
Cassiopeia Ace	590	105		5:32	5:32	6:48	1:16	8:09	14:57	1:14	15:52	16:11	16:21	16:49	0:10	0:28	0:38	0	1:16	18:05	19:57	1:52		-19:57
Daiten	738	105		6:29	6:29	8:21	1:52	3:25	11:46	1:20	13:10	13:06	13:15	14:06	0:09	0:51	1:00	1	0:20	14:26	16:12	1:46		-16:12
Jinsei Maru	651	105		6:58	6:58	8:14	1:16	4:06	12:20	1:07	13:49	13:27	14:09	14:49	0:42	0:40	1:22	1	0:31	15:20	16:48	1:28		-16:48
Crusader Venture	730	105		8:24	8:24	10:16	1:52	3:07	13:23	1:11	14:30	14:34	14:43	15:33	0:09	0:50	0:59	0	0:50	16:23	17:55	1:32		-17:55
Marlenvoy	731	105		9:07	9:07	11:22	2:15	2:15	13:37	1:22	15:03	14:59	15:16	16:25	0:17	1:09	1:26	1	0:27	16:52	19:02	2:10		-19:02
Oceanic Success	590	100		7:09	7:09	8:43	1:34	3:28	12:11	1:10	13:30	13:21	13:44	14:33	0:23	0:49	1:12	1	0:21	14:54	15:48	0:54		-15:48
Co-op Granel	736	105		7:53	7:53	9:55	2:02	2:21	12:16	1:28	13:46	13:44	13:53	14:42	0:09	0:49	0:58	1	0:21	15:03	16:12	1:09		-16:12
Goya	731	105		8:17	8:17	10:36	2:19	2:34	13:10	1:22	14:07	14:32	14:48	15:45	0:16	0:57	1:13	0	0:37	16:22	17:29	1:07		-17:29
Regno Marinas	685	105		7:40	7:40	9:09	1:29	3:16	12:25	1:33	14:04	13:58	14:09	14:53	0:11	0:44	0:55	1	0:14	15:07	16:00	0:53		-16:00
Chi Hui	731	105		8:05	8:05	10:08	2:03	2:54	13:02	1:18	14:26	14:20	14:32	15:21	0:12	0:49	1:01	1	0:24	15:45	16:57	1:12		-16:57
Liberty Spirit	738	105		9:16	9:16	11:02	1:46	2:26	13:28	1:41	15:07	15:09	15:22	16:16	0:13	0:54	1:07	0	0:26	16:42	18:10	1:28		-18:10
Traviata	623	105		11:27	11:27	13:09	1:42	2:06	15:15	1:01	16:27	16:16	16:43	17:26	0:27	0:43	1:10	1	1:21	18:47	20:25	1:38		-20:25
BP Argosy	578	101		5:54	5:54	7:14	1:20	3:04	10:18	1:09	11:14	11:27	11:34	12:03	0:07	0:29	0:36	0	0:15	12:18	13:06	0:48		-13:06
OT Moonlight	630	105		6:17	6:17	7:45	1:28	2:38	10:23	1:18	11:47	11:41	11:50	12:24	0:09	0:34	0:43	1	0:18	12:42	13:38	0:56		-13:38
Pelagos	777	105		7:31	7:31	9:28	1:57	2:10	11:38	1:11	12:32	12:49	13:00	13:40	0:11	0:40	0:51	0	0:25	14:05	15:13	1:08		-15:13
Ballesti	721	105		8:11	8:11	10:06	1:55	1:55	12:01	1:05	12:54	13:06	13:14	13:55	0:08	0:41	0:49	0	0:20	14:15	15:24	1:09		-15:24
Zim Savannah	738	106		9:41	9:41	11:10	1:29	1:27	12:37	1:10	13:50	13:47	14:00	14:39	0:13	0:39	0:52	1	0:47	15:26	16:29	1:03		-16:29
Ocean Friend	734	105		10:28	10:28	12:11	1:43	1:49	14:00	0:56	14:49	14:56	15:05	15:43	0:09	0:38	0:47	0	0:19	16:02	17:02	1:00		-17:02
Canada Express	740	100		4:16	4:16	5:31	1:15	5:56	11:27	0:54	12:15	12:21	12:29	12:57	0:08	0:28	0:36	0	0:15	13:12	14:04	0:52		-14:04
Maipo	666	105		4:34	4:34	5:58	1:24	5:33	11:31	1:04	12:35	12:35	12:44	13:08	0:09	0:24	0:33	0	0:16	13:24	14:18	0:54		-14:18
Forest Hawk	711	105		5:51	5:51	7:11	1:20	4:33	11:44	1:17	13:10	13:01	13:15	13:46	0:14	0:31	0:45	1	0:26	14:12	15:10	0:58		-15:10
Jo Red Wood	573	105		6:17	6:17	7:42	1:25	4:23	12:05	1:28	13:18	13:33	13:43	14:21	0:10	0:38	0:48	0	0:17	14:38	15:34	0:56		-15:34
Ming Pleasure	884	105		7:33	7:33	9:00	1:27	3:50	12:50	1:12	14:10	14:02	14:13	14:48	0:11	0:35	0:46	1	0:37	15:25	16:23	0:58		-16:23
Hudson Bay	721	105		9:12	9:12	11:29	2:17	2:18	13:47	1:12		14:59	15:07	15:47	0:08	0:40	0:48	0	0:24	16:11	17:16	1:05		-17:16
Guinomar Trader	748	105		9:33	9:33	11:40	2:07	2:27	14:07	1:14	14:49	15:21	15:32	16:15	0:11	0:43	0:54	0	0:33	16:48	17:49	1:01		-17:49

TABLE A-1 (cont'd)

Tandem

Name of ship	V/L L	Dim B	Leave Balboa	Tn1	Miraflores Locks Arrive	Leave	Tn2	Miraflores Lake Tn3	Pedro Miguel Locks Loco Arr. Time	V/L Arrived	V/L Entered	V/L Cleared	Tn4(a)	Tn4(b)	Tn4	Late Loco arr.	Gaillard Cut Pass Gamboa	Tn5	Gatun Lake Tn6	Gatun Locks Arrive	Leave	Tn7	Arrive Cristobal	Tn8
Rep Del Ecuador	511	69		18:05	18:05	18:56	0:51	0:11	19:00	19:07	19:14	19:53	0:07	0:39	0:46	0	20:36	0:43	2:22	22:58	0:30	1:32		-0:30
Sea Royal	234	12		18:13	18:13	19:00	0:47	0:13	19:00	19:13	19:20	19:57	0:07	0:37	0:44	0	20:37	0:40	2:47	23:24	0:34	1:10		-0:34
Tropical Mist	491	70		20:21	20:21	21:20	0:59	0:18	21:33	21:38	21:52	22:40	0:14	0:48	1:02	0	23:30	0:50	1:38	1:08	2:38	1:30		-2:38
Sun Isabel	275	40		20:34	20:34	21:22	0:48	0:35	21:33	21:57	22:04	22:43	0:07	0:39	0:46	0	23:33	0:50	1:55	1:28	2:41	1:13		-2:41
Mickie Birdsall	462	82		8:49	8:49	9:34	0:45	0:22	10:03	9:56	10:11	10:45	0:15	0:34	0:49	1	11:35	0:50	2:35	14:10	15:59	1:49		-15:59
Courageous	136	40		0:00			0:00	9:56	10:03	9:56	10:11	10:45	0:15	0:34	0:49	1		-10:45	0:00			0:00		0:00
George N	418	62		17:58	17:58	18:44	0:46	0:17	18:55	19:01	19:07	19:33	0:06	0:26	0:32	0	20:26	0:53	2:09	22:35	23:59	1:24		-23:59
Soshin Maru No.33	183	29		18:03	18:03	18:47	0:44	0:19	18:55	19:06	19:13	19:35	0:07	0:22	0:29	0	20:28	0:53	2:17	22:45	0:00	1:35		0:00
Potomac	496	70		19:17	19:17	20:08	0:51	0:22	22:44	20:30	20:37	21:01	0:07	0:24	0:31	1	21:45	0:44	1:40	23:25	0:39	1:14		-0:39
Ana Maria	290	42		19:27	19:27	20:12	0:45	0:12	22:44	20:24	20:31	20:59	0:07	0:28	0:35	1	21:46	0:47	2:28	0:14	1:12	0:58		-1:12
Ecuadorian Reefer	473	79		7:56	7:56	8:50	0:54	0:36	9:26	9:26	9:39	10:13	0:13	0:34	0:47	0	11:44	1:31	3:24	15:08	16:49	1:41		-16:49
Dalmar Servant	193	39		7:56	7:56	8:50	0:54	0:36	9:26	9:26	9:39	10:13	0:13	0:34	0:47	0	11:44	1:31	3:24	15:08	16:49	1:41		-16:49
Ohyoh	410	53		17:58	17:58	18:52	0:54	0:16	19:55	19:08	19:18	19:44	0:10	0:26	0:36	1	20:29	0:45	3:26	23:55	1:42	1:47		-1:42
Ryoei Maru No.78	183	29		18:09	18:09	18:54	0:45	0:14	19:55	19:08	19:18	19:44	0:10	0:26	0:36	1	20:33	0:49	2:10	22:43	0:26	0:43		-0:26
Catano	264	53		7:40	7:40	8:43	1:03	0:31	9:15	9:14	9:35	10:17	0:21	0:42	1:03	1	11:37	1:20	3:13	14:50	16:49	1:59		-16:49
El Reno Grande	100	27		0:00			0:00	9:14	9:15	9:14	9:35	10:17	0:21	0:42	1:03	1		-10:17	0:00			0:00		0:00
Ionian Mariner	444	63		8:45	8:45	9:37	0:52	1:07	10:41	10:44	10:51	11:20	0:07	0:29	0:36	0	12:05	0:45	9:15	21:20	22:32	1:12		-22:32
Windborne	51	13		0:00			0:00	10:53	10:41	10:53	10:59	11:20	0:06	0:21	0:27	0		-11:20	0:00			0:00		0:00
Spring Delight	499	73		16:18	16:18	17:00	0:42	0:24	17:13	17:24	17:31	17:59	0:07	0:28	0:35	0	18:58	0:59	3:43	22:41	23:59	1:18		-23:59
Daito Maru No.7	212	28		16:22	16:22	17:12	0:50	0:17	17:13	17:29	17:36	18:01	0:07	0:25	0:32	0	19:00	0:59	3:36	22:36	23:53	1:17		-23:53
Asian Reefer	473	79		17:19	17:19	18:14	0:55	0:20	18:30	18:34	18:43	19:16	0:09	0:33	0:42	0	20:16	1:00	2:07	22:23	0:06	0:43		-0:06
Enterprise	212	39		17:30	17:30	18:17	0:47	0:29	18:30	18:46	18:53	19:17	0:07	0:24	0:31	0	20:21	1:04	2:15	22:36	0:11	0:35		-0:11
Hannoverland	487	71		17:44	17:44	19:13	1:29	0:13	19:28	19:26	19:31	20:01	0:05	0:30	0:35	1	20:41	0:40	3:21	0:02	1:42	1:40		-1:42
Dae Sung No.7	177	29		18:32	18:32	19:15	0:43	0:20	19:28	19:35	19:41	20:03	0:06	0:22	0:28	0	20:55	0:52	3:40	0:35	1:45	1:10		-1:45
Pearle Jahn	540	80		7:05	7:05	7:49	0:44	0:36	8:45	8:25	8:49	9:11	0:24	0:22	0:46	1	9:57	0:46	5:33	15:30	16:40	1:10		-16:40
Betty Cultreath	120	31		0:00			0:00	8:25	8:45	8:25	8:49	9:11	0:24	0:22	0:46	1		-9:11	0:00			0:00		0:00
Key Biscayne	420	80		16:51	16:51	17:46	0:55	0:09	17:30	17:55	18:02	18:39	0:07	0:37	0:44	0	19:19	0:40	1:39	20:58	22:26	1:28		-22:26
kofu Maru	367	53		17:00	17:00	17:52	0:52	0:19	17:30	18:11	18:17	18:42	0:06	0:25	0:31	0	19:26	0:44	1:47	21:13	22:31	1:18		-22:31
South Sheilds	482	72		18:12	18:12	19:03	0:51	0:19	19:00	19:22	19:28	19:50	0:06	0:22	0:28	0	20:44	0:54	2:21	23:05	1:00	1:55		-1:00
Don Bollinger	155	36		18:18	18:18	19:05	0:47	0:21	19:00	19:26	19:31	19:53	0:05	0:22	0:27	0	20:44	0:51	2:08	22:52	0:02	1:10		-0:02
Halcion	65	19		9:22	9:22	10:03	0:41	0:25	9:20	10:28	10:32	10:55	0:04	0:23	0:27	0		-10:55	0:00			0:00		0:00
Egret	41	19		9:22	9:22	10:03	0:41	0:25	9:20	10:28	10:32	10:55	0:04	0:23	0:27	0		-10:55	0:00			0:00		0:00
Sadie	36	19		9:22	9:22	10:03	0:41	0:25	9:20	10:28	10:32	10:55	0:04	0:23	0:27	0		-10:55	0:00			0:00		0:00
Walter Jacob	479	70		17:35	17:35	18:24	0:49	0:12	18:33	18:36	18:42	19:07	0:06	0:25	0:31	0	19:56	0:49	3:29	23:25	0:38	1:13		-0:38
Shoshin Maru No.82	183	29		17:42	17:42	18:25	0:43	0:15	18:33	18:40	18:46	19:04	0:06	0:18	0:24	0	19:57	0:53	3:39	23:36	0:41	1:05		-0:41
Bergen	399	57		19:34	19:34	20:20	0:46	0:16	20:24	20:36	20:41	20:59	0:05	0:18	0:23	0	21:46	0:47	3:12	0:58	2:14	1:16		-2:14
Shinsei Maru No.3	175	28		19:40	19:40	20:22	0:42	0:10	20:24	20:32	20:37	20:59	0:05	0:22	0:27	1	21:43	0:44	3:31	1:14	2:18	1:04		-2:18

Name of ship	V/L L	Dim B	Leave Cristobal	Ts1	Gatun Locks Arrive	Leave	Ts2	Gatun Lake Ts3	Gaillard Cut Pass Gamboa	Ts4	Pedro Miguel Locks Loco Arr. Time	V/L Arrived	V/L Entered	V/L Cleared	Ts5 (a)	Ts5 (b)	Ts5	Late Loco arr.	Miraflores Lake Ts6	Miraflores Locks Arrive	Leave	Ts7	Arrive Balboa	Ts8
Moku Dahu	134	80		4:49	4:49	6:13	1:24	5:28	11:41	1:07	12:36	12:48	12:56	13:42	0:08	0:46	0:54	0	0:22	14:04	14:51	0:47		-14:51
HSTC 1	639	84		0:00			0:00	0:00		12:48	12:36	12:48	12:56	13:42	0:08	0:46	0:54	0	-13:42			0:00		0:00
Balsa 9	351	57		18:17	18:17	20:02	1:45	2:07	22:09	1:19		23:28	23:35	0:08	0:07	0:33	0:40	0	0:16	0:24	1:11	0:47		-1:11
Janne Terkol	274	44		18:54	18:54	20:05	1:11	1:50	21:55	1:17		23:12	23:25	0:04	0:13	0:39	0:52	0	0:12	0:16	1:07	0:51		-1:07
Chiquita Bocas	554	78		10:12	10:12	11:30	1:18	2:05	13:35	1:15	14:53	14:50	15:03	15:36	0:13	0:33	0:46	1	0:45	16:21	17:12	0:51		-17:12
6EPB7758	65	18		0:00			0:00	0:00		14:32	14:53	14:32	15:01	15:31	0:29	0:30	0:59	1	-15:31			0:00		0:00
6EPB7735	65	18		0:00			0:00	0:00		14:32	14:53	14:32	15:01	15:31	0:29	0:30	0:59	1	-15:31			0:00		0:00
Tama Hope	477	61		17:09	17:09	18:28	1:19	2:13	20:41	1:14	22:01	21:55	22:04	22:39	0:09	0:35	0:44	1	0:25	23:04	23:55	0:51		-23:55
Baltimar Apollo	299	48		17:20	17:20	18:32	1:12	2:13	20:45	1:21	22:01	22:06	22:12	22:41	0:06	0:29	0:35	0	0:30	23:11	23:59	0:48		-23:59
Zodiak	419	67		18:48	18:48	20:12	1:24	1:54	22:06	0:59		23:05	0:27	0:44	1:22	0:17	1:39	0	0:00	0:44	1:30	0:46		-1:30
Frio Espana	340	52		19:00	19:00	20:16	1:16	1:34	21:50	1:15		23:05	0:27	0:44	1:22	0:17	1:39	0	-0:11	0:33	1:29	0:56		-1:29
Khalij Frost	461	65		17:38	17:38	18:49	1:11	1:28	20:17	1:23	21:35	21:40	21:46	22:18	0:06	0:32	0:38	0	0:16	22:34	23:19	0:45		-23:19
Emelie	300	49		17:43	17:43	18:51	1:08	1:52	20:43	1:02	21:35	21:45	21:50	22:20	0:05	0:30	0:35	0	1:03	23:23	0:01	0:38		-0:01
Orion Reefer	472	70		18:59	18:59	20:09	1:10	1:26	21:35	1:00	23:20	22:35	23:23	0:01	0:48	0:38	1:26	1	0:11	0:12	1:02	0:50		-1:02
Tadorne II	271	52		19:08	19:08	20:14	1:06	1:55	22:09	1:22	23:20	23:31	23:32	0:03	0:01	0:31	0:32	0	0:17	0:20	1:04	0:44		-1:04
Blue Tank Lancer	361	57		20:28	20:28	21:53	1:25	2:02	23:55	1:06	1:03	1:01	1:21	1:44	0:20	0:23	0:43	1	0:09	1:53	2:41	0:48		-2:41
Penelope 1	337	48		20:43	20:43	21:56	1:13	2:18	0:14	0:47	1:03	1:01	1:21	1:44	0:20	0:23	0:43	1	0:14	1:58	2:44	0:46		-2:44
Chaiten	498	77		16:44	16:44	17:55	1:11	1:26	19:21	1:03	20:11	20:24	20:24	20:54	0:00	0:30	0:30	0	0:13	21:07	22:58	1:51		-22:58
Vanessa	280	45		16:48	16:48	18:00	1:12	1:34	19:34	0:47	20:11	20:21	20:28	20:56	0:07	0:28	0:35	0	1:11	22:07	23:00	0:53		-23:00
Merkur Beach	492	68		18:11	18:11	19:24	1:13	1:34	20:58	0:58	22:01	21:56	22:14	22:48	0:18	0:34	0:52	1	0:14	23:02	23:52	0:50		-23:52
Daitoku Maru No.55	179	28		18:21	18:21	19:27	1:06	2:03	21:30	0:44	22:01	22:14	22:21	22:52	0:07	0:31	0:38	0	0:18	23:10	23:55	0:45		-23:55
Karlois Dozhelah	396	62		17:50	17:50	19:05	1:15	1:41	20:46	1:33	22:17	22:19	22:20	22:58	0:01	0:38	0:39	0	0:14	23:12	0:04	0:52		-0:04
Rio Salado	350	47		17:59	17:59	19:09	1:10	1:52	21:01	1:28	22:17	22:29	22:39	23:03	0:10	0:24	0:34	0	0:15	23:18	0:09	0:51		-0:09
Balsa 32	349	53		19:29	19:29	20:43	1:14	1:56	22:39	0:58	23:20	23:37	23:45	0:14	0:08	0:29	0:37	0	0:16	0:30	1:18	0:48		-1:18
San Pancracio I	290	45		19:43	19:43	20:48	1:05	1:51	22:39	1:09	23:20	23:48	23:54	0:18	0:06	0:24	0:30	0	0:18	0:36	1:22	0:46		-1:22
Simon Bolivar	521	81		12:00	12:00	13:22	1:22	1:48	15:10	1:20	16:24	16:30	16:31	16:57	0:01	0:26	0:27	0	1:30	18:27	19:43	1:16		-19:43
The Muster	36	10		12:00	12:00	13:24	1:24	-13:24		16:30	16:24	16:30	16:31	16:57	0:01	0:26	0:27	0	-16:57			0:00		0:00
Cisne	67	25		12:00	12:00	13:24	1:24	-13:24		16:30	16:24	16:30	16:31	16:57	0:01	0:26	0:27	0	-16:57			0:00		0:00
Delmonte Trans	462	73		16:24	16:24	17:40	1:16	1:24	19:04	0:45	19:46	19:49	20:18	20:48	0:29	0:30	0:59	0	0:39	21:27	22:14	0:47		-22:14
Delfin II	123	24		16:24	16:24	17:42	1:18	-17:42		19:49	19:46	19:49	20:18	20:48	0:29	0:30	0:59	0	-20:48			0:00		0:00

TABLE A-2
OBSERVED VESSEL LOCKAGE TIMES

Miraflores Lock
Regular Lockage

Vessel Size (Beam in ft) (Draft in ft)	Approach time (min)	Entry time (min)	Chamber time (min)	Exit time (min)	Sum time (min)	Ship Name
Up to 60					40	PCC Standard Time
60-69	5	6	29	4	44	Nikolay Karamzin
	5	6	32	5	48	American Gulf I
	5	7	25	4	41	Bonita
	5	6	29	4	44	Average
					40	PCC Standard Time
70-79	13	7	30	4	54	Merchant Premier
	10	8	25	6	49	Peony Islands
	12	8	28	5	52	Average
					45	PCC Standard Time
80-89	5	7	25	8	45	Barbara Vaught
	5	7	26	5	43	Lakambini
	8	9	25	6	48	Hua Jin
	6	8	25	6	45	Average
					50	PCC Standard Time
80-89 (36' up)					50	PCC Standard Time
90-99	11	9	29	9	58	Nippon Highway
					55	PCC Standard Time
90-99 (30'-36')	7	7	29	8	51	Bing He
					65	PCC Standard Time
90-99 (36'-39.6')	11	13	35	9	68	Samuel H. Armocost
					70	PCC Standard Time
100 (Ballast)	2	12	36	5	55	Glorious Ace
	2	14	33	4	53	Tian Tan Hai
	2	13	35	5	54	Average
					60	PCC Standard Time
100 (30'-36')					70	PCC Standard Time
100 (36'-38')					80	PCC Standard Time
100 (38' & over)					85	PCC Standard Time
100 (Deeply laden)					95	PCC Standard Time
Tandem	5	9	29	5	48	Cevo
	4	4	29	8	45	Taiho Maru #7
	5	12	32	2	51	Railro
	5	6	32	5	48	Sierra Guadarrama
	5	14	27	3	49	Kenkyu Maru #18
	4	6	27	6	43	Chiquita Bocas
	5	9	29	5	47	Average
					50	PCC Standard Time

Miraflores Lock
Relay Lockage

Vessel Size (Beam in ft) (Draft in ft)	Approach time (min)	Entry time (min)	Chamber time (min)	Exit time (min)	Sum time (min)	Ship Name
60-69					30	PCC Standard Time
70-79					30	PCC Standard Time
80-89	12	6	29	5	52	Virginia
					40	PCC Standard Time
80-89 (36' up)					40	PCC Standard Time
90-99	9	8	23	5	45	Esmeraldos
					40	PCC Standard Time
90-99 (30'-36')	8	10	29	8	55	Neptune Sirius
					45	PCC Standard Time
90-99 (36'-39.6')					50	PCC Standard Time
100 (Ballast)					45	PCC Standard Time
100 (30'-36')					50	PCC Standard Time
100 (36'-38')	29	15	32	7	83	Santa Maria
					60	PCC Standard Time
100 (Deeply laden)						
Tandem					40	PCC Standard Time

TABLE A-2 (cont'd)

Pedro Miguel Lock
Regular Lockage

Vessel Size (Beam in ft) (Draft in ft)	Approach time (min)	Entry time (min)	Chamber time (min)	Exit time (min)	Sum time (min)	Ship Name
Up to 60	11	5	12	4	32	Inger Riis
					30	PCC Standard Time
60-69	7	6	16	5	34	New Zealand Reefer
	12	8	12	6	38	Cai Lun
	11	6	13	4	34	American Gulf I
	10	7	14	5	35	Average
					30	PCC Standard Time
70-79	10	8	13	8	39	Peony Islands
	12	7	13	4	36	Merchant Premier
	11	8	13	6	38	Average
					30	PCC Standard Time
80-89	7	6	13	4	30	Barbara Vaught
	7	9	12	5	33	Lakambini
	7	8	13	5	32	Average
					40	PCC Standard Time
80-89 (36' up)					40	PCC Standard Time
90-99	9	9	14	5	37	Nippon Highway
					40	PCC Standard Time
90-99 (30'-36')	34	9	11	9	63	DSR Oakland
	10	8	13	11	42	Bing He
	22	9	12	10	53	Average
					45	PCC Standard Time
90-99 (36'-39.6')	10	10	13	11	44	Samuel H. Armacost
					50	PCC Standard Time
100 (Ballast)	14	11	13	10	48	Glorious Ace
	11	9	12	4	36	American Senator
	16	8	10	5	39	Western Future
	8	8	12	8	36	Tian Tan Hai
	12	9	12	7	40	Average
					40	PCC Standard Time
100 (30'-36')					50	PCC Standard Time
100 (36'-38')					60	PCC Standard Time
100 (38' & over)					60	PCC Standard Time
100 (Deeply laden)					70	PCC Standard Time
Tandem	5	11	11	3	30	Merkur Lake
	5	5	11	6	27	Tumaco
	5	8	11	5	29	Average
					40	PCC Standard Time

Gatun Lock
Regular Lockage

Vessel Size (Beam in ft) (Draft in ft)	Approach time (min)	Entry time (min)	Chamber time (min)	Exit time (min)	Sum time (min)	Ship Name
Up to 60					60	PCC Standard Time
60-69					60	PCC Standard Time
70-79	7	5	42	4	58	Indian Ocean
					60	PCC Standard Time
80-89	8	8	41	5	62	Republic de Columbi
	8	7	44	5	64	Isabel Barreto
	8	8	43	5	63	Average
					70	PCC Standard Time
80-89 (36' up)					70	PCC Standard Time
90-99					70	PCC Standard Time
90-99 (30'-36')	14	10	46	6	76	Jo Brevik
					75	PCC Standard Time
90-99 (36'-39.6')					85	PCC Standard Time
100 (Ballast)	14	12	60	6	92	Ocean Highway
	10	6	46	6	68	Century Highway #1
	15	5	47	5	72	Eagle
	13	8	51	6	77	Average
					70	PCC Standard Time
100 (30'-36')	9	21	54	9	93	Ever Garden
					85	PCC Standard Time
100 (36'-38')	11	13	65	10	99	OUCL Fair
					105	PCC Standard Time
100 (38' & over)	42	27	101	10	180	Evniki
	40	11	75	11	137	Sirena
	13	10	69	15	107	Myrina
	32	16	82	12	141	Average
					120	PCC Standard Time
100 (Deeply laden)					130	PCC Standard Time
Tandem					70	PCC Standard Time

TABLE A-3
PCC SHIP DATA BANK RECORDS

Basic Ship Information File Layout (YY0200O)[1]

FIELD NAME	LENGTH	FROM	TO	REMARKS
Ship Number	6	1	6	
Ship Name	30	7	36	
Ship Type Code	2	37	38	
Length	6	39	44	FT 9(4)V99
Beam	5	45	49	FT 9(3)V99
Maximum Tropical Fresh Water Draft	8	50	57	FIND 9(8)
Panama Canal Commission Maximum Authorized Draft	4	58	61	FTIN 9(4)
Horsepower Type	1	62	62	
Horsepower Rating	6	63	68	9(6)
Summer Dead Weight	6	69	74	LTW 9(6)
Immersion	4	75	78	TPI 9(3)V9
Nonstandard Transit Rules	1	79	79	
Preferential Transit	1	80	80	
Tie-up Restrictions	1	81	81	
Daylight Transit - Regular	1	82	82	
Daylight Transit - Draft	1	83	83	
Full Daylight - Regular	1	84	84	
Daylight in Cut - Regular	1	85	85	
Daylight in Cut - Draft	1	86	86	
Clearcut - Regular	1	87	87	
Clearcut - 170 ft. Rule	1	88	88	
Clear Channel - Gatun Locks to Buoy 13	1	89	89	

[1] Variables are defined in PCC Data Processing System Manual No. 16.

Basic Ship Information File Layout (YY0200O - cont'd)

FIELD NAME	LENGTH	FROM	TO	REMARKS
Clear Channel - Balboa Basin to Buoy 13	1	90	90	
Clear Channel - Balboa Basin to Bridge	1	91	91	
Clear Channel - Miraflores Locks to Buoy 1 - Draft	1	92	92	
Clear Channel - Miraflores Locks to Buoy 1 - Night	1	93	93	
Maximum Speed in Canal	3	94	96	KT* 9(2)V9

UNITS

FT = Feet - FF'

FIND = Feet, inches, numerator, denominator - FF' IN" NN/DD

FTIN = Feet, inches - FF' IN"

LTW = Long tons weight

TPI = Tons per inch

KT* = Knots to the nearest .0 or .5

TABLE A-3 (cont'd)

Transit Information File Layout (YY0201O)

FIELD NAME	LENGTH	FROM	TO	REMARKS
Ship Number	6	1	6	
Ship Name	30	7	36	
Arrival Date	6	37	42	YMD
Arrival Time	4	43	46	HM
Transit Direction	1	47	47	
Delay Code	1	48	48	
Transit Restrictions	1	49	49	
Ready to Transit Date	6	50	55	YMD
Ready to Transit Time	4	56	59	HM
Transit Underway Date	6	60	65	YMD
Transit Underway Time	4	66	69	HM
Transit Booking	1	70	70	
Transit Beginning Date	6	71	76	YMD
First set of locks				
Arrival Time	4	77	80	HM
Entry Time	4	81	84	HM
Clear Time	4	85	88	HM
Departure Time	4	89	92	HM
Pedro Miguel Locks				
Arrival Time	4	93	96	HM
Entry Time	4	97	100	HM
Clear Time	4	101	104	HM
Departure Time	4	105	108	HM

Transit Information File Layout (YY0201O - cont'd)

FIELD NAME	LENGTH	FROM	TO	REMARKS
Last set of locks				
Arrival Time	4	109	112	HM
Entry Time	4	113	116	HM
Clear Time	4	117	120	HM
Departure Time	4	121	124	HM
Departure Date	6	125	130	YMD
Gamboa Sight Time	4	131	134	HM
Gamboa Passing Time	4	135	138	HM
Transit Termination Date	6	139	144	YMD
Transit Termination Time	4	145	148	HM
Tropical Fresh Water Forward Draft	4	149	152	FTIN
Tropical fresh Water After Draft	4	153	156	FTIN

UNITS

YMD = Year, month, day YYMMDD

HM = Hours, minutes HH:MM

FTIN = Feet, inches - FF' IN"

TABLE A-4
APPROACH AND LOCKAGE TIMES FROM SDB RECORDS

Vsl. Class	Dir.	No. Vsl.	Times at Gatun Locks (minutes)							
			Approach				Lockage			
			Avg.	SD	Min.	Max.	Avg.	SD	Min.	Max.
1	N	1066	16.41	18.59	1.00	126	62.88	10.20	11.0	162
	S	1145	8.74	8.01	1.00	71	60.88	9.30	7.00	126
2	N	567	15.67	16.07	2.00	98	60.26	7.66	3.20	94
	S	547	10.89	10.52	1.00	95	59.48	8.41	8.00	94
3	N	1385	15.56	15.42	1.00	260	60.84	7.80	5.00	156
	S	1387	11.02	10.22	1.00	122	59.67	7.91	10.0	126
4	N	561	17.84	18.74	1.00	250	62.80	10.90	3.00	241
	S	534	12.90	11.42	2.00	99	62.32	8.60	48.0	174
5	N	40	19.55	17.37	6.00	99	66.50	7.21	42.0	83
	S	7	12.86	12.35	6.00	40	63.71	6.13	58.0	76
6	N	269	20.53	18.88	4.00	193	65.30	9.67	1.00	138
	S	243	14.43	11.26	3.00	61	64.29	8.20	51.0	96
7	N	233	22.75	17.77	1.00	112	68.67	6.69	55.0	93
	S	286	16.43	14.91	2.00	110	69.13	8.23	50.0	102
8	N	134	19.67	15.95	2.00	82	75.15	8.52	61.0	103
	S	143	15.93	13.41	2.00	90	76.54	14.66	10.0	130
9	N	446	23.00	17.47	2.00	190	70.15	9.60	42.0	123
	S	357	16.57	12.91	3.00	78	70.06	11.07	52.0	159
10	N	477	22.87	17.11	2.00	102	78.55	10.29	55.0	132
	S	381	16.84	12.70	3.00	110	75.73	10.81	11.0	147
11	N	0	--	--	--	--	--	--	--	--
	S	177	17.72	13.25	5.00	73	84.72	11.65	22.0	128
12	N	273	21.06	16.74	4.00	90	97.19	13.72	61.0	197
	S	661	18.17	12.88	3.00	75	105.93	14.05	31.0	179

TABLE A-4 (cont'd)

Vsl. Class	Dir.	No. Vsl.	Times at Pedro Miguel Locks (minutes)							
			Approach				Lockage			
			Avg.	SD	Min.	Max.	Avg.	SD	Min.	Max.
1	N	1066	7.92	8.42	1.00	144	26.19	26.64	13.0	498
	S	1145	10.30	9.82	1.00	79	25.46	8.25	1.00	126
2	N	567	8.55	6.52	2.00	68	24.10	6.25	11.0	139
	S	547	9.82	9.30	3.00	146	25.69	8.92	2.00	152
3	N	1385	8.82	6.82	2.00	146	24.77	6.08	1.00	132
	S	1387	10.36	7.64	2.00	63	26.11	11.51	10.0	298
4	N	561	9.54	6.48	3.00	96	26.43	20.12	5.00	469
	S	534	11.23	7.38	4.00	60	27.07	9.45	20.0	177
5	N	40	9.12	3.38	5.00	26	29.25	4.01	24.0	48
	S	7	17.57	15.46	6.00	50	26.86	1.57	25.0	29
6	N	269	12.00	8.00	3.00	57	29.10	15.77	20.0	188
	S	243	12.13	7.23	5.00	44	28.52	9.14	3.00	105
7	N	233	11.85	8.75	3.00	56	30.40	9.10	22.0	107
	S	286	11.56	7.33	5.00	72	30.47	7.09	7.00	96
8	N	134	12.18	6.31	6.00	48	35.71	21.46	19.0	222
	S	143	11.13	5.22	5.00	35	34.01	6.17	26.0	67
9	N	446	14.02	10.14	4.00	70	30.90	14.33	17.0	164
	S	357	12.83	7.50	5.00	50	29.18	7.33	5.00	111
10	N	477	14.88	12.56	3.00	113	33.93	9.81	18.0	139
	S	381	13.14	7.40	4.00	52	34.14	6.29	26.0	97
11	N	0	--	--	--	--	--	--	--	--
	S	177	12.23	5.59	5.00	43	37.24	4.67	24.0	52
12	N	273	13.13	8.67	5.00	100	47.89	9.23	31.0	160
	S	661	13.09	7.30	5.00	67	42.75	7.10	22.0	123

TABLE A-4 (cont'd)

Vsl. Class	Dir.	No. Vsl.	Times at Miraflores Locks (minutes)							
			Approach				Lockage			
			Avg.	SD	Min.	Max.	Avg.	SD	Min.	Max.
1	N	1066	7.67	7.65	1.00	105	42.89	9.92	11.0	151
	S	1145	10.14	11.88	1.00	114	40.40	7.20	2.00	108
2	N	567	7.26	3.11	3.00	51	41.05	6.12	31.0	76
	S	547	8.87	8.19	2.00	63	40.02	5.13	29.0	77
3	N	1385	8.87	8.73	2.00	110	41.15	6.04	9.00	110
	S	1387	9.38	8.36	1.00	77	40.43	5.05	20.0	88
4	N	561	9.65	7.48	3.00	59	42.08	5.37	24.0	74
	S	534	11.01	10.16	3.00	73	41.94	5.51	33.0	79
5	N	40	9.25	4.78	5.00	29	46.45	4.84	41.0	66
	S	7	10.71	6.02	6.00	21	40.57	5.06	36.0	51
6	N	269	11.15	8.86	4.00	112	44.09	4.88	35.0	65
	S	243	14.21	13.71	4.00	69	42.03	7.03	34.0	108
7	N	233	10.93	5.25	5.00	33	46.87	5.56	29.0	72
	S	286	15.33	14.70	4.00	77	44.84	4.83	37.0	76
8	N	134	11.51	5.50	5.00	34	51.40	6.27	39.0	75
	S	143	13.79	12.24	4.00	76	48.70	7.22	38.0	111
9	N	446	13.12	6.59	4.00	56	47.91	5.99	33.0	89
	S	357	17.32	14.30	4.00	80	44.62	6.32	31.0	92
10	N	477	13.56	7.17	5.00	63	53.30	7.37	38.0	104
	S	381	15.31	11.50	4.00	66	49.82	7.02	39.0	118
11	N	0	--	--	--	--	--	--	--	--
	S	177	15.01	12.20	3.00	75	54.20	6.80	42.0	96
12	N	273	14.31	6.52	5.00	50	70.98	8.50	49.0	101
	S	661	13.65	10.14	4.00	71	63.66	8.73	6.00	12.5

TABLE A-5
AVERAGE VALUES OF DRT BY VESSEL TYPE AND TRANSIT DIRECTION

Trans. Direct.	Vessel Type	Sample Size	Mean (hrs)	Std. Dvn.	Min.	Max.
N	1	1098	4.381	6.191	0.00	24.00
N	2	549	2.888	4.838	0.00	22.66
N	3	1376	2.711	4.829	0.00	24.00
N	4	547	2.547	4.774	0.00	23.33
N	5	40	0.903	1.028	0.00	6.95
N	6	285	2.166	4.279	0.00	23.91
N	7	257	1.337	2.184	0.13	16.03
N	8	146	1.128	1.696	0.10	11.50
N	9	473	1.684	3.222	0.00	20.21
N	10	363	1.611	3.223	0.01	23.78
N	11	118	1.225	2.124	0.16	17.20
N	12	275	1.289	2.253	0.08	20.16
N	13	44	1.858	4.496	0.00	23.50
N	14	41	7.403	7.148	0.01	22.00
All NB	-	5612	2.664	4.750	0.00	24.00
S	1	1297	4.576	6.289	0.00	24.00
S	2	527	3.748	5.595	0.00	24.00
S	3	1341	3.314	5.227	0.00	24.00
S	4	511	3.026	4.996	0.00	24.00
S	5	129	3.791	5.316	0.08	21.50
S	6	210	2.321	4.322	0.00	22.25
S	7	270	2.436	4.172	0.00	23.16
S	8	147	1.976	3.799	0.00	22.80
S	9	355	2.316	4.380	0.00	23.96
S	10	373	2.179	3.699	0.00	21.93
S	11	169	1.845	3.167	0.05	22.41
S	12	642	1.739	3.210	0.00	23.08
S	13	89	1.307	2.776	0.00	14.66
S	14	36	10.802	8.569	0.50	24.00
All SB	-	6096	3.182	5.168	0.00	24.00

TABLE A-6
AVERAGE VALUES OF DUT BY VESSEL TYPE AND TRANSIT DIRECTION

Trans Direct.	Vessel Type	Sample Size	Mean (hrs)	Std. Dvn.	Min.	Max.
N	1	1247	6.802	6.459	0.0	23.833
N	2	531	7.594	6.372	0.0	23.916
N	3	1304	7.298	5.812	0.0	23.833
N	4	512	8.261	6.539	0.0	24.000
N	5	37	9.180	6.909	0.1	23.516
N	6	258	9.876	6.296	0.0	23.450
N	7	241	10.367	6.179	0.0	23.666
N	8	139	9.592	6.721	0.0	24.000
N	9	455	9.924	6.440	0.0	23.950
N	10	347	8.872	5.927	0.0	23.416
N	11	114	9.048	5.900	0.0	23.750
N	12	244	10.366	6.379	0.0	23.066
N	13	46	0.698	1.265	0.0	6.250
N	14	238	2.385	3.584	0.0	24.000
All NB	-	5713	7.831	6.388	0.0	24.000
S	1	1427	7.183	6.606	0.0	24.000
S	2	496	7.311	6.303	0.0	23.866
S	3	1278	7.255	6.193	0.0	23.833
S	4	457	7.881	6.717	0.0	24.000
S	5	117	7.571	6.558	0.0	23.416
S	6	195	9.579	6.945	0.0	24.000
S	7	254	8.560	6.051	0.0	23.750
S	8	129	9.577	6.502	0.0	23.750
S	9	323	10.896	6.950	0.0	23.833
S	10	350	10.101	6.053	0.0	23.966
S	11	150	10.231	6.666	0.0	23.833
S	12	533	10.409	6.997	0.0	23.816
S	13	96	0.611	1.616	0.0	9.083
S	14	384	4.360	3.250	0.0	23.333
All SB	-	6189	7.883	6.568	0.0	24.000

TABLE A-7
TRANSIT TIMES THROUGH SEGMENT 1

Trans Dir.	Vessel Type	No. of Ships	Mean Time (hrs)	Std. Dvn. (hrs)	Min. (hrs)	Max. (hrs)
N	1	885	0.656	0.186	0.500	1.983
N	2	424	0.622	0.147	0.500	1.833
N	3	1144	0.647	0.163	0.500	1.750
N	4	538	0.658	0.171	0.500	1.833
N	5	40	0.666	0.184	0.500	1.416
N	6	274	0.629	0.120	0.500	1.400
N	7	252	0.664	0.123	0.500	1.200
N	8	146	0.660	0.101	0.500	1.400
N	9	455	0.632	0.117	0.500	1.700
N	10	346	0.642	0.126	0.500	1.233
N	11	117	0.706	0.166	0.500	1.600
N	12	282	0.714	0.111	0.500	1.400
N	13	42	0.596	0.100	0.500	0.916
N	14	167	0.820	0.239	0.500	1.700
All NB	-	5112	0.657	0.161	0.500	1.983
S	1	1462	1.187	0.329	0.500	2.000
S	2	579	1.197	0.295	0.566	2.000
S	3	1452	1.193	0.295	0.500	2.000
S	4	536	1.253	0.297	0.583	2.000
S	5	129	1.301	0.295	0.633	1.966
S	6	223	1.223	0.306	0.633	2.000
S	7	282	1.270	0.312	0.583	2.000
S	8	148	1.292	0.301	0.800	1.983
S	9	376	1.221	0.281	0.633	1.983
S	10	377	1.215	0.274	0.633	1.966
S	11	174	1.215	0.265	0.616	1.950
S	12	647	1.227	0.252	0.633	2.000
S	13	89	1.255	0.334	0.683	1.966
S	14	279	1.269	0.345	0.533	2.000
All SB	-	6753	1.216	0.302	0.500	2.000

TABLE A-8
TRANSIT TIMES THROUGH SEGMENT 2

Trans Dir.	Vessel Type	No. of Ships	Mean Time (hrs)	Std. Dvn. (hrs)	Min. (hrs)	Max. (hrs)
N	1	1028	3.317	1.175	1.500	5.983
N	2	418	3.689	1.223	1.500	6.000
N	3	955	3.562	1.219	1.500	6.000
N	4	386	3.555	1.233	1.500	6.000
N	5	21	3.500	0.943	1.966	5.633
N	6	188	3.830	1.112	1.533	5.950
N	7	160	3.745	1.122	1.500	5.866
N	8	89	3.458	1.093	1.533	5.633
N	9	363	3.825	1.027	1.516	5.916
N	10	307	3.610	0.952	1.516	6.000
N	11	95	3.416	0.894	1.600	5.816
N	12	206	3.230	0.953	1.533	5.800
N	13	37	2.702	0.659	1.583	4.066
N	14	113	3.108	0.985	1.500	5.316
All NB	-	4366	3.520	1.556	1.500	6.000
S	1	1353	2.274	0.812	1.500	5.983
S	2	485	2.331	0.972	1.500	6.000
S	3	1216	2.351	0.977	1.500	6.000
S	4	498	2.426	1.016	1.500	5.950
S	5	116	2.387	0.764	1.633	5.283
S	6	200	2.912	1.273	1.516	5.950
S	7	255	2.981	1.240	1.500	6.000
S	8	134	2.803	1.050	1.700	5.566
S	9	345	3.038	1.174	1.500	5.900
S	10	359	2.985	1.071	1.500	5.966
S	11	165	2.653	0.898	1.500	5.783
S	12	633	2.546	0.773	1.500	5.950
S	13	57	2.226	0.678	1.500	4.700
S	14	82	2.434	0.645	1.500	3.900
All SB	-	5898	2.504	0.994	1.500	6.000

TABLE A-9
TRANSIT TIMES THROUGH SEGMENT 3

Trans Dir.	Vessel Type	No. of Ships	Mean Time (hrs)	Std. Dvn. (hrs)	Min. (hrs)	Max. (hrs)
N	1	1284	1.157	0.586	0.500	3.000
N	2	521	1.142	0.536	0.533	2.816
N	3	1285	1.191	0.551	0.583	2.950
N	4	542	1.239	0.577	0.600	2.933
N	5	34	1.404	0.614	0.850	2.950
N	6	292	1.297	0.572	0.733	2.983
N	7	254	1.489	0.657	0.683	2.950
N	8	145	1.539	0.677	0.850	2.933
N	9	487	1.366	0.615	0.700	2.966
N	10	362	1.390	0.603	0.733	2.966
N	11	119	1.441	0.655	0.716	3.000
N	12	273	1.488	0.645	0.883	3.000
N	13	45	1.322	0.649	0.683	2.716
N	14	178	1.416	0.499	0.550	2.916
All NB	-	5821	1.266	0.597	0.500	3.000
S	1	1544	1.186	0.340	0.550	2.900
S	2	594	1.197	0.300	0.533	2.550
S	3	1483	1.209	0.293	0.500	2.733
S	4	562	1.215	0.268	0.616	3.000
S	5	136	1.346	0.260	0.883	2.433
S	6	233	1.160	0.205	0.683	2.016
S	7	295	1.228	0.232	0.733	2.583
S	8	152	1.252	0.188	0.800	2.000
S	9	381	1.228	0.235	0.766	2.433
S	10	384	1.283	0.240	0.633	2.683
S	11	177	1.275	0.229	0.783	2.166
S	12	670	1.322	0.227	0.750	2.866
S	13	60	1.211	0.306	0.716	2.150
S	14	328	1.401	0.390	0.550	2.883
All SB	-	6999	1.233	0.294	0.500	3.000

TABLE A-10
TRANSIT TIMES THROUGH SEGMENT 4

Trans. Dir.	Vessel Type	No. of Ships	Mean Time (hrs)	Std. Dvn. (hrs)	Min. (hrs)	Max. (hrs)
N	1	912	0.368	0.136	0.25	1.000
N	2	380	0.365	0.149	0.25	0.983
N	3	1062	0.362	0.140	0.25	1.000
N	4	479	0.368	0.131	0.25	0.916
N	5	38	0.368	0.081	0.25	0.583
N	6	246	0.399	0.162	0.25	1.000
N	7	241	0.400	0.139	0.25	1.000
N	8	142	0.436	0.156	0.25	1.000
N	9	434	0.425	0.171	0.25	1.000
N	10	312	0.425	0.172	0.25	1.000
N	11	113	0.431	0.142	0.25	1.000
N	12	278	0.423	0.139	0.25	0.983
N	13	40	0.373	0.119	0.25	0.783
N	14	136	0.398	0.153	0.25	0.983
All NB	-	4813	0.387	0.149	0.25	1.000
S	1	896	0.416	0.164	0.25	1.000
S	2	429	0.394	0.163	0.25	1.000
S	3	1149	0.387	0.153	0.25	1.000
S	4	462	0.391	0.156	0.25	1.000
S	5	123	0.405	0.114	0.25	0.833
S	6	189	0.412	0.163	0.25	0.983
S	7	262	0.424	0.169	0.25	1.000
S	8	134	0.431	0.149	0.25	0.983
S	9	320	0.415	0.156	0.25	1.000
S	10	345	0.408	0.137	0.25	0.966
S	11	170	0.428	0.141	0.25	1.000
S	12	654	0.423	0.123	0.25	0.983
S	13	48	0.446	0.152	0.25	0.850
S	14	83	0.386	0.166	0.25	0.916
All SB	-	5264	0.407	0.153	0.25	1.000

TABLE A-11
TRANSIT TIMES THROUGH SEGMENT 5

Trans. Dir.	Vessel Type	No. of Ships	Mean Time (hrs)	Std. Dvn. (hrs)	Min. (hrs)	Max. (hrs)
N	1	1239	1.240	0.368	0.266	2.000
N	2	550	1.344	0.314	0.383	2.000
N	3	1331	1.334	0.347	0.333	2.000
N	4	512	1.382	0.386	0.416	2.000
N	5	33	1.521	0.304	0.733	1.966
N	6	256	1.437	0.327	0.466	2.000
N	7	215	1.527	0.267	0.550	1.983
N	8	117	1.581	0.257	0.833	2.000
N	9	417	1.570	0.257	0.566	2.000
N	10	304	1.578	0.234	0.783	2.000
N	11	100	1.595	0.194	1.083	2.000
N	12	229	1.654	0.208	0.983	2.000
N	13	36	1.384	0.263	0.866	1.866
N	14	158	1.149	0.381	0.300	2.000
All NB	-	5497	1.382	0.355	0.270	2.000
S	1	1546	0.799	0.224	0.250	1.916
S	2	594	0.846	0.153	0.416	1.950
S	3	1489	0.852	0.143	0.250	1.733
S	4	564	0.909	0.154	0.266	1.716
S	5	137	0.967	0.130	0.500	1.366
S	6	232	0.884	0.113	0.283	1.333
S	7	295	0.932	0.117	0.383	1.533
S	8	152	0.984	0.116	0.600	1.600
S	9	380	0.911	0.120	0.433	1.766
S	10	383	0.926	0.114	0.450	1.650
S	11	176	0.974	0.136	0.766	1.950
S	12	670	1.021	0.115	0.433	1.716
S	13	97	0.751	0.216	0.416	1.400
S	14	346	0.797	0.260	0.250	1.566
All SB	-	7061	0.877	0.182	0.250	1.950

APPENDIX B

MODEL "LATIS"

APPENDIX B

MODEL "LATIS"

1. INTRODUCTION

Mathematical models are efficient tools in engineering. They enable engineers to compare several alternatives within a short period of time and help them to arrive at the best solution. However, several theoretical assumptions and idealizations are made during the development of these models. The user must be aware of these assumptions and the limitations in the use of these models. The model "LATIS" is no exception to this rule. In the following pages we have tried to explain the important features in the development of the model. The mathematical formulation and the governing equations are explained in Section 2. The advantages and disadvantages in using either the implicit or the explicit schemes in solving the governing equations are then discussed. In Section 4, the stability criterion, the Courant condition, is explained. The necessary data that has to be used and the program PRELATIS that is used to create the data is elaborated in Section 5. The final section, Section 6, describes the procedure used to present the results in graphical form.

2. MATHEMATICAL PROCEDURE USED IN LATIS

The continuity equation for gradually varied, unsteady flow may be written for a node i connected to N channels of a network (Figure B-1):

$$\sum_{j=1}^{N} Q_{ji} = A_i \frac{\partial H_i}{\partial t} \tag{1}$$

in which Q_{ji} = the discharges (positive when entering the node) of the channels (or links) at the connections with the node; and A_i = the surface area ascribed to the node which is assumed constant and horizontal during time interval dt, but otherwise a function of H_i, the water surface elevation with respect to a given datum.

The dynamic equation for one of the links of the network may be written:

$$\frac{\partial H}{\partial x} = -\frac{1}{g}\frac{\partial V}{\partial t} - \frac{|Q|Q}{K^2} - \frac{V}{g}\frac{\partial V}{\partial x} \tag{2}$$

in which x = the abscissa along the link; V = the mean velocity; Q = the discharge; and K = the conveyance, a function of H.

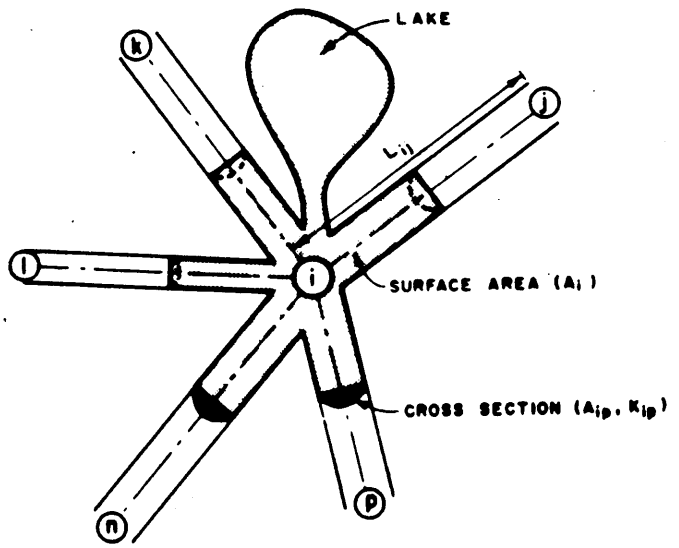

FIGURE B-1 -- NODE AND LINK DEFINITIONS

Equations 1 and 2 are not linear, but do not contain terms with products of the derivatives. Linearization and finite difference translation of Equations 1 and 2 to render the system amenable to solution, depend on the definition of the unknowns involved in each equation, and the time levels (t, t – Δt, t – 2Δt, t – 3Δt) used in the computation.

Orlob, Shubinski, et al. (6,7) have formulated "direct explicit" models expressing all coefficients and space derivatives in terms of values of the dependent variables computed on the time interval just before the unknown values, i.e. at time t – Δt, which are considered only in the time derivatives. This results in a rectangular computational scheme. Although a direct explicit scheme may be inherently unstable in a one-dimensional case (9), it has proven successful in networks.

The procedure used for Program LATIS (explicit) computes all variables at the same time, t, using for the definition of the coefficients and the space derivatives values computed for one and two previous time intervals t – Δt and t – 2Δt. In addition, as in Program FAT, and according to the linearization scheme of Dronkers (3) the friction term is computed with the product of the "new" (i.e. at time t) discharge and that obtained for t – 2Δt.

To define the time derivatives, use is made of the difference between the functional values at times t and t - 2Δt.

To obtain the hydraulic variables for the internal (t) – (t – 2Δt) a weighed value is obtained.

$$H^{(t-1)+a} = \frac{H^{(t-1)} - H^{(t-2)}}{\Delta t}(1+a)\Delta t + H^{(t-2)} = (1+a)H^{(t-1)} - aH^{(t-2)} \tag{3}$$

Referring to water surface elevation in which the constant, a, may be positive or negative and is less than 1 in absolute value. A similar relation is obtained for Q. In Equation 3 and in the following, the superscripts refer to the time interval corresponding to the value of the variable: t = the "new" time for which the unknown is computed; t − 1 refers to time t − Δt; and t − 2 refers to time t − 2Δt.

The computation schedule results in the following finite difference continuity and dynamic equations for the gradually varied unsteady flow:

$$2\Delta t \sum_{j=1}^{N} [(1+a)\, Q_{ij}^{(t-1)} - aQ_{ij}^{(t-2)}] = [(1+a)\, A_i^{(t-1)} - aA_i^{(t-2)}]\,(H_i^{(t)} - H_i^{(t-2)} \tag{4}$$

$$[(1+a)H_j^{(t-1)} - aH_j^{(t-2)}] - [(1+a)H_i^{(t-1)} - aH_i^{(t-2)}]$$

$$= -\frac{L_{ij}(Q_{ij}^{(t)} - Q_{ij}^{(t-2)}}{2g\Delta t\,[(1+a)A_{ij}^{(t-1)} - aA_{ij}^{(t-2)}]} - \frac{L_{ij}|Q_{ij}^{(t-2)}|Q_{ij}^{(t)}}{\{CALIB\,[(1+a)K_{ij}^{(t-1)} - aK_{ij}^{(t-2)}]\}^2}$$

$$- \frac{[(1+a)Q_{ij}^{(t-1)} - aQ_{ij}^{(t-2)}]}{2g\,[(1+a)A_{ij}^{(t-1)} - aA_{ij}^{(t-2)}]} \left[\frac{(1+a)Q_{jk}^{(t-1)} - aQ_{jk}^{(t-2)}}{(1+a)A_{jk}^{(t-1)} - aA_{jk}^{(t-2)}} - \frac{(1+a)Q_{li}^{(t-1)} - aQ_{li}^{(t-2)}}{(1+a)A_{li}^{(t-1)} - aA_{li}^{(t-2)}}\right] \tag{5}$$

in which Δt = the time interval; superscripts mean time instant; single and double subscripts mean node and link, respectively; N = the number of links connected at a node; Q = the discharge through a link; A with a single subscript = the surface area of a node (a function of its water surface elevation); and A with two subscripts, represents the cross-sectional area of a link (a function of the average water surface elevations of its adjacent nodes); H = the water surface elevation above a datum; L = the length; and K = the conveyance of a link (a function of the average water surface elevations of its adjacent nodes). Value CALIB is equal to the ratio of the Manning's coefficient used in determining K and a revised value

that may be required for calibration that is to adjust the solution to a known condition of the system.

In Equation 5 the left-hand side member is the water surface elevation difference between nodes i and j, assumed for the interval, $2\Delta t = (t) - (t - 2\Delta t)$; the first term of the right-hand side member is the local inertia term due to the change in discharge in link ij during that interval; the second term is the linearized friction; and the third term represents the convective inertia, which is expressed as a function of the difference in velocities for links jk and li, adjacent to the link ij. The structure of this term implies that only one link is connected at either end of link ij and that its velocity is not modified by a constriction. Therefore, it is omitted when more than one link are connected or when there is a constriction.

The preceding equations assume that the rate of flow, computed at mid-distance of the nodes defining the link, is an accurate approximation of the discharge in the link, which in fact varies between the two nodes.

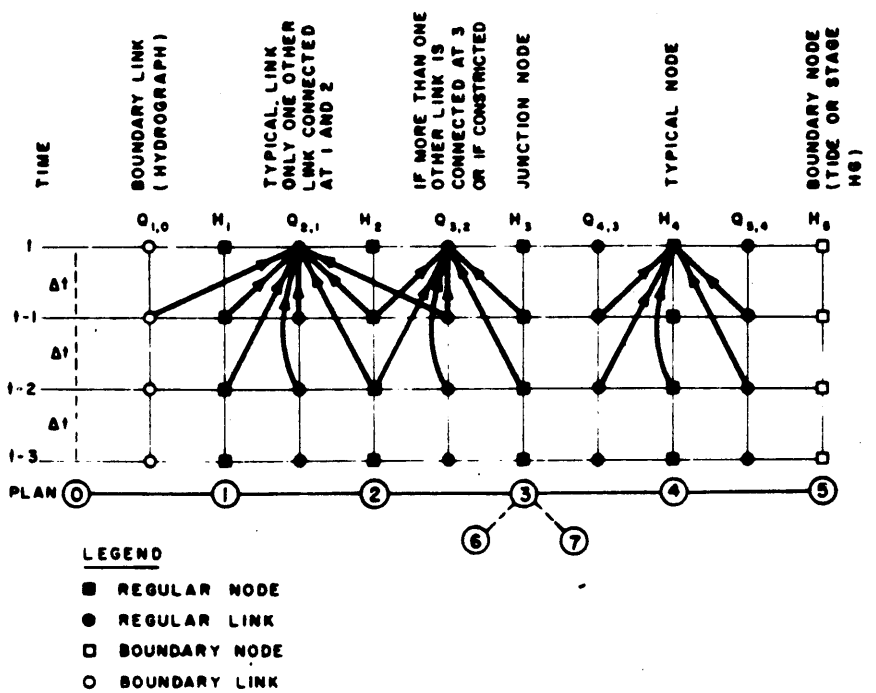

FIGURE B-2 -- LATIS COMPUTATION SCHEDULE

Each one of these equations has only one unknown, $H_{(i)}^{(t)}$ or $Q_{if}^{(t)}$, and the system formed for all nodes and links allows their determination one by one. In other words, the coefficient matrix has only its diagonal as nonzero terms. Figure B-2 is a graph of the computation schedule where the arrows show the variables used in the computation of each "new" and simultaneous value of H and Q. The introduction of weighted average values using the results of two consecutive time intervals

and the introduction of the unknown discharge in the definition of the friction are probably conducive to better stability than in the case of the direct explicit scheme in a one-dimensional system.

The aforementioned procedure is general and may be applied to multiple or simply connected networks. In LATIS, the network may be one dimensional or assumed formed by either triangular or quadrangular elements.

If a node receives an independent inflow (pump, tributary) a pseudolink is added, having a specified discharge hydrograph. If the water surface elevation at a node is governed by a specified time law, this is a pseudonode. Pseudolinks and nodes are boundary conditions of the network.

When there is a constriction in a link, equations similar to those developed in previous analyses of one-dimensional flow in open channels (1) are written for the time of Equations 4 and 5, using weighted values of the "previous" discharges and elevations.

For the application of Equation 4 to node i, discharges are considered positive when flowing into the node. For the application of Equation 5, discharges are considered positive when flowing into the lower numbered node. Since the first rule is absolute while the second depends on the arbitrary labeling of the nodes, a bookkeeping procedure is needed to change the signs as required in case of conflict.

3. IMPLICIT VERSUS EXPLICIT SCHEMES

Equations 1 and 2 are not linear but do not contain terms with products of the derivatives. To solve them they will be expressed in finite differences and linearized. The quadratic term in the discharge in Equation 1 is substituted by the product of the unknown discharge at time t and the discharge computed one (or two) time intervals before for the same channel reach, which reduces the term to a linear one. The other non-linear terms are similarly linearized by using previously computed values of the variables in a recursive form.

When the space derivatives are defined in terms of the unknown values of the variables, the resulting system of linear equations is implicit, that is, each equation contains more than one unknown. If the space derivatives are defined in terms of previously computed values of the unknowns, each equation contains only one unknown, provided by the temporal derivative, or by the friction term, and the system is explicit.

There are advantages and disadvantages to each system. Implicit systems are unconditionally stable, independently of the time interval. Consequently, relatively long time intervals may be used, which reduces the number of operations and

allows for the representation of long periods of real time with reasonable computer times. Explicit systems are subject to the Courant condition, which imposes a limit to the integration time interval, depending on the depth and length of the channel reach and, in general, they are more suitable for relatively short real time representations. Implicit systems are somewhat difficult to modify once the network is defined and unless the matrices are tridiagonal, each solution may consume a considerable amount of computer time, which tends to compensate for the savings obtained by increasing the time interval and, therefore, decreasing the number of solutions for a given integration.

In addition to the Courant condition, which applies to the explicit solution, there is a limitation on the time increment which applies also to implicit solution. When parts of the network are gradually flooded, long term intervals are conducive to solution "blowups" if the volumes of water which flow through a link during the time interval are large in comparison with the capacity available at the node being flooded.

Instabilities may appear also when models present abrupt changes in hydraulic or topographic characteristics, such as reach length, conveyance, cross-sectional area, depth, flood plain width and area, etc.

4. STABILITY CRITERIA

The Mathematical Model was formulated using Program LATIS which had been used in a number of previous network analyses, and has been continuously revised to extend its range of application. LATIS is explicit, so it is subject to the Courant condition which, for the LATIS procedure, may be written:

$$\Delta t < \frac{L_{ij}}{2\,(V + \sqrt{g y_{ij}}\,)}$$

in which: Δt is the time interval; L_{ij}, the reach (or link) ij length; V_{ij}, the maximum absolute value of the velocity in the link; g, the acceleration due to gravity; y_{ij}, the depth.

5. INPUT DATA

The channel hydraulic characteristics are computed with an auxiliary program: PRELATIS, which processes up to five cross-sections per link. These cross-sections are input as tables of coordinates of up to 30 points with up to 29 different values of Mannings 'n'. The program then computes cross-sectional areas and conveyances for each cross-section and obtains representative areas and conveyances for the link by averaging the values obtained for each cross-section at discrete elevations. These average values are printed and punched in LATIS format.

PRELATIS also computes the steady state uniform flow corresponding to each link using the bottom slope. This feature is useful to establish a plausible value of water surface elevation for initial condition estimates. Finally, PRELATIS may compute the volumes of the link at each elevation. This is desirable when salinity studies are coupled with a hydraulic study. In that case LATIS may use volumes instead of areas in the continuity equation of each link. The volumes are then computed as the sum of one-half of each of the volumes computed for each link connected to the node at each elevation.

Further, Mannings 'n', simulation time interval, the accuracy required, and other output options are also included in the input data set. For example, in analyzing the Vergara solution, the bay area was assumed to consist of several elements. These were included in the node definition card in the data file.

6. OUTPUT

When the model is run it creates two files: an output file consisting of all the data and results and a plot file consisting of variables that can be used to create graphical outputs such as the time series of velocities in a canal at a given location. The plot file is then imported into the LOTUS program and the velocities, or the water surface elevations as predicted by the model can be plotted. The titles for the graph and other enhancements for the graphical display can be made at this point.

APPENDIX C

ABS REPORT

APPENDIX C

ABS REPORT

The recommendations herein were prepared by ABS Marine Services, Inc., acting through Captain Wilbur H. Vantine.

The recommended transit requirements herein are based on a number of assumptions:

1. That for normal speed navigation, there be leading channel ranges visible to the pilots. Providing this facility would require that the channels be laid out with small course changes of about seven or eight degrees every four or five miles. During periods of poor visibility, when these ranges would not be visible, speeds would have to be reduced.

2. There should be no sharp turns and the channel should be significantly wider at the bends.

3. The width of the channels will be three times the beam of the largest ship for single-lane traffic and seven times the beam for two-way traffic.

4. The depth of the channel will be at least 10% greater than the allowed draft.

5. A transit requirement should be that ships displacing over 75,000 tons be required to have sterns constructed so that a tug can be made up there on the center line to assist the ship in the channels (Panama Canal "Cut" style).

6. That, in addition to the tugs assigned to work on the stern of transiting ships, additional tugs should be available on a standby basis to assist on the bows of vessels should it be necessary to slow or stop traffic due to an emergency.

7. Tugs assigned to assist vessels of 75,000 tons and over be of at least 6,000 horsepower, preferably of the "tractor type" with approximately equal thrust in all directions.

Further, the recommendations that follow are for ships loaded to the stated displacements.

These recommendations are on the conservative side and are suitable for start-up operations. After experience over a period of time, it may be possible to reduce some of these requirements, particularly the speed limitations.

The handling characteristics for 250,000 and 300,000 DWT vessels are about the same.

Ships under 45,000 DWT could be dispatched at ten minute intervals with a reasonable safety factor.

RECOMMENDED TRANSIT REQUIREMENTS

A. 150,000 DWT VESSELS

1. SINGLE LANE (one-way traffic)

   a. Maximum speed over the ground -- 8 knots

   b. Maximum allowed head current -- 2 knots

   c. Maximum allowed following current -- 1 knot

   d. Tug assistance (on stern) -- optional

   e. Spacing behind leading ship:
      - with slack water or head current -- 15 minutes
      - with following current -- 20 minutes

2. DOUBLE LANE (two-way traffic)

   a. Maximum speed over the ground:
      - when running free -- 10 knots;
      - when meeting other large ships -- 6 to 7 knots

   b. Maximum allowed head current -- 2 knots

   c. Maximum allowed following current - 1 knot

   d. Tug assistance (on stern) -- mandatory

   e. Spacing behind leading ship:
      - with slack water or head current -- 15 minutes
      - with following current -- 20 minutes

B. 250,000 AND 300,000 DWT VESSELS

1. SINGLE LANE (one-way traffic)

   a. Maximum speed over the ground -- 6 to 7 knots

   b. Maximum allowed head current -- 2 knots

   c. Maximum allowed following current -- 1 knot

   d. Tug assistance (on stern) -- mandatory

   e. Spacing behind leading ship:
      - with slack water or head current -- 20 minutes
      - with following current -- 30 minutes

2. DOUBLE LANE (two-way traffic)

   a. Maximum speed over the ground:
      - when running free -- 8 knots
      - when meeting other large ships -- 4 to 5 knots

   b. Maximum allowed head current -- 2 knots

   c. Maximum allowed following current -- 1 knot

   d. Tug assistance (on stern) -- mandatory

   e. Spacing behind leading ship:
      - with slack water or head current -- 20 minutes
      - with following current -- 30 minutes

APPENDIX D

WATERWAY ANALYSIS MODEL

APPENDIX D

WATERWAY ANALYSIS MODEL

WATERWAY SYSTEM REPRESENTATION

The following paragraphs describe the way in which the various elements of the inland navigation system are represented in the Waterway Analysis Model. Waterways and waterway facilities are discussed first, followed by sections on vessel and cargo representation.

The Waterway Network

(1) Network Structure

The waterway network is represented in the simulation model as a hierarchy of elements:

- River Systems
  - Sectors
    - Ports
    - Locks
      - Chambers
    - Bend Terminators
    - Reaches
    - Bends

In model terminology, ports, locks, and bend terminators are often referred to as nodes because they represent points, as opposed to bends and reaches which have length and are referred to as links. Sectors and river systems serve to organize these lower level elements into convenient units for processing and analysis.

(2) Ports

Port operations are represented only through average processing times. Only two types of activities occur at a port, barge loading and unloading, and barge pick-up and drop-off by towboats.

Each port in the system is described by numeric identifiers, port name, river mile, tow stopping delay, barge pick-up/drop-off delay, and the port's loading and unloading rate. The tow stopping delay simulates the time required by a towboat to drop off or pick up barges. It represents an "overhead" time to secure a fleet of barges to the towboat to form a tow. The barge pick-up/drop-off delay represents the time in hours per barge to reconfigure a group of barges when being picked up or dropped off by a towboat. The total delay at a port for a towboat is the sum of the tow stopping delay plus the product of the barge pick-up/drop-off delay and the number of barges involved in the exchange. The loading/unloading rates can be port and commodity specific, and are used to estimate the corresponding barge processing times.

(3) Locks

Lock and dam facilities are generally waterway elements of direct interest to navigation planners because of the large expenditure of public funds they represent and because they are frequently the bottlenecks of the system. Consequently, locks are represented at a comparatively detailed level relative to the rest of the waterway network.

Lock data are inserted into the network in order of appearance of the lock within each sector and locks are treated as specific points in the network. Locks are represented by name, number, and river mile location.

Recreational traffic can also be represented at a lock. Its input consists of a recreational lockage policy and a recreational traffic rate. The lockage policy gives the maximum number of commercial lockages a recreation vessel could wait, before having access to the lock, while the recreational traffic rates give the average number of recreation vessels locked daily.

(4) Lock Chambers

Chamber data are input to the network immediately following the lock data. The input consists of a chamber number, dimensions (width and length) in feet, the normal operating policy designation, and the probability of a single lockage being a setover.

Immediately following the chamber data records, lockage time distributions for the chamber are input. The time required to complete the movement of a tow through the lock is determined from this information. At an actual lock, this time varies with a large number of factors including size and configuration of the tow, maneuverability, water level, current speed, presence of interfering traffic, weather conditions, and pilot skill. Accounting for all such factors explicitly in a model is clearly infeasible. A common simulation

tactic is therefore employed. A small subset of the most important factors are selected for explicit representation, then the influence of the remaining factors is treated as a random variation described by a probability distribution.

The factors explicitly considered by the model in calculating lockage times are:

- the type of lockage - straight single, setover (the model classes all single lockages requiring reconfiguration as setovers), multiple-cut, multiple-vessel, or open pass;
- the direction of travel - upstream or downstream;
- the type of entry to and exit from the chamber - fly, turnback, or exchange.

Lock processing time is subdivided into four components: approach, entry, chambering, and exit. Probability distributions for each component under the various conditions given above are input to the model as data. The user may specify common analytical distributions (such as normal, gamma or Weibull distributions), or may enter tabulated empirical frequency distributions. The process of simulating a lockage consists of selecting the appropriate distribution for each component, drawing a random sample from each, and summing to get the total processing time.

The preceding discussion has been concerned with modeling the actual passage of vessels through a lock. An equally important facet of lock operations involves the queuing of vessels which cannot be passed immediately and the associated rules for determining the order of service, and selection of chambers at a multichamber lock facility. The model supports "first come-first serve," "N up-N down," and "one-way" operating policies for each chamber. A queue is maintained for the lock facility as a whole. Tows are assigned chambers as they become available.

(5) Reaches

A reach, as the term is used in the simulation model, is an unrestricted section of waterway between two ports, two locks, two bend terminators, a port and a lock, a port and a bend terminator, or a lock and a bend terminator. A reach, along with a bend, are the only network elements with a nonzero length.

The physical characteristics of a reach which affect tow speeds include current velocity, depth, channel width, radius of bends, and presence of ob-

stacles. The first two of these are represented explicitly in the model. All other influences are aggregated into a pair of coefficients called tow speed coefficients, one for each direction of travel. These coefficients may be estimated by comparing theoretical and observed tow speeds, and taking into account the specific channel conditions described above.

The size of a tow may be limited by the dimensions of the navigation channel. In the model, a tow size limit is specified for each sector. A particularly restricted portion of the waterway may be modeled by changing that portion of the waterway from being a reach to a bend.

(6) Bend Terminators

A bend terminator is that point on a section of waterway where a reach (unrestricted as far as the tow traffic is concerned) becomes a bend (restricted as far as the tow traffic is concerned). Bend terminators are represented by number and river mile location.

When a tow arrives at a bend terminator entering a bend, the simulation model makes a determination as to whether or not the tow may enter the bend based upon other tow traffic in the bend or approaching the bend and the characteristics of the bend. If the tow is not allowed to immediately enter the bend, it is queued at the bend terminator point until such a time as the tow may enter the bend.

(7) Bends

A bend, as the term is used in the simulation model, is a restricted section of waterway between two bend terminators. A bend does not necessarily have a radius of curvature, since a narrow channel may also be represented in the model by a bend.

The physical characteristics of a bend which affect tow speeds include current velocity, depth, channel width, radius of the bend, and presence of obstacles. The first two are modeled explicitly while all other influences are aggregated into a pair of coefficients called tow speed coefficients, one for each direction of travel. In addition, a flanking speed coefficient is used when the length of a tow is such that a flanking maneuver is required in order for the tow to transit a given bend. The channel width, radius of bend, required clearance for two-way traffic, tow length, and tow width are all explicitly represented in the model in order to determine whether or not a tow is delayed from entering a bend or narrow channel and, once delayed, when a tow may enter the bend or narrow channel.

Bends are modeled assuming that a tow in a bend cannot overtake and pass another tow in the bend that is traveling in the same direction. The model further assumes that the following tow will maintain a separation distance of at least two tow lengths.

(8) Other Features

Other features and facilities present in the actual waterway system, such as marinas, docks, navigation aids, etc., are substantially less significant to inland navigation and are not explicitly represented in the model. Their effects can often be implicitly accounted for through such parameters as port processing times and reach speed coefficients. Indeed, it may be difficult or impossible to obtain data which exclude such effects.

Vessels

Towboats and barges are the active waterway traffic elements in the model. Towboats and barges are organized into classes with all vessels of the same class treated as being identical.

(1) Towboats

Each class of towboat represented in the model is described by its horsepower, dimensions, towing capacity, a 20-character name, and a numeric identifier. The first two characteristics are used in the computation of tow speed. The towing capacity places an upper limit on the size of tow that can be moved by the boat.

Towboat classes and all parameters describing a particular class are user input. Therefore, it is possible to simulate many types of unique towboats. Currently the model limits to ninety-nine (99) the total number of towboat classes which can be represented.

(2) Barges

Barge classes are described by their size and the amounts of various classes of cargo they can carry. For purposes of computing towing speeds and fitting tows into lock chambers, the barge dimensions -- length, width and draft, are employed. The model permits the capacity of each type of barge to be specified separately for each class of commodity. A capacity of zero indicates a mismatch between barge and commodity class. In addition, the model takes the channel depth along the route of shipment into account when simulating the loading of barges. If the barge cannot be loaded to its full draft, its capacity is reduced proportionally.

(3) Recreational Craft

Tows share the waterways with other vessels, all of which are classified as recreational craft in the model. The model is not concerned with these vessels per se, but only with their influence on commercial traffic. The most significant interaction occurs at locks and this is the only place where the model takes notice of recreational traffic.

Recreational craft are assumed to appear randomly, at a specified average rate, at locks where they are to be simulated. Each vessel is represented explicitly during the time it waits for and accomplishes its lockage; then, as far as the model is concerned, it disappears from the system. Movement of recreational craft between locks is not represented. There is no differentiation among sizes or types of recreational vessels.

The arrival rate of recreational craft is specified separately for each lock where they are to be taken into account. Separate rates for weekends and weekdays are provided, as well as for upstream and downstream directions of travel. Arrivals may be limited to a specific period during the day (daylight hours, for example) to further represent the uneven distribution of recreational traffic observed in practice.

Cargo

Demands for cargo shipment provide the driving force for the simulation model, in response to which all other activity takes place. The stream of shipment demands is an external input to the model.

(1) Commodity Classes

The many commodities transported in the actual system are aggregated in the model into commodity classes. Each commodity class requires input information relative to the types of barges which may carry the class, the density of loading of the class and whether or not the class is considered hazardous cargo. (No tow containing hazardous cargo may be locked through with any other vessel.) Each commodity class is assigned to a commodity group.

(2) Commodity Groups

Commodity classes are aggregated into commodity groups to reduce the amount of computer storage required. Commodity groups are used to assign loading/unloading rates for all commodity classes contained in the group. They are specified for each group and optionally, for any commodity group and port combination.

(3) Shipment List

The shipment list is a stream of shipment demands which is input to the model during execution. Each demand is described by a commodity class, tonnage, shipment origin, shipment destination, time of availability, type of towboat, type of barge, number of loaded barges, and number of empty barges. The origins and destinations of the shipments are the ports discussed earlier.

The form in which commodity flow data are available to the user will generally not be as a set of shipment demands as required by the model, but as an origin-destination matrix giving the total flows (by commodity) between pairs of ports over a period of time. A user-provided preprocessor program is generally used to convert such a matrix to the separate shipments needed by the model.

MODEL OPERATIONS

Representing the physical elements of a system is only one part of a simulation model. Equally important is representing the operating rules of the system. This section describes the operations of the WAM. The discussion is at a logical, rather than at the program level.

Cargo and Barge Operations

(1) Cargo Arrival

The activity of the simulated system begins when cargo arrives at a port for shipment to another port. The simulation program's external event mechanism invokes the corresponding processing routine automatically at the simulated time when each shipment is due to enter the system. (Note that the term "shipment" refers, in the model, to the cargo described by a single shipment data record.)

(2) Cargo Loading and Unloading

A basic assumption of the model is that the required number of barges of the types specified is available at the origin port at the time the cargo is available. The key computation here is the capacity of each barge. A maximum capacity for each feasible combination of barge class and commodity type is available from the input data; however, it may be necessary to reduce this figure because inadequate depth along the shipping route limits the usable draft of the barges. As part of the initial processing of each shipment, the minimum depth on the anticipated route is located and stored. With this information, plus the barge attributes of empty draft, fully loaded

draft, and required bottom clearance, it is a straightforward calculation to obtain the maximum permissible loading, assuming that draft increases linearly with tonnage.

Loading continues with computation of the time required. The tonnage to be loaded is divided by the applicable loading rate to get the loading time for the barges. The entire group of barges being considered is assumed to be loaded as a unit, all barges becoming available for pickup at the same time.

Although the process by which barges are moved to their destination has not yet been discussed, it is appropriate at this point to consider the activity which takes place upon their arrival. If the barges are loaded, the first task is to unload them and record the delivery of the cargo. Unloading is similar to loading with respect to selecting the appropriate unloading rate and computing the time required.

(3) Tow Movements

The movement of shipments through the waterway network is in many ways the heart of the model. The basic mechanism involved is a simple process of advancing a location indicator associated with each shipment from one element (port, lock, bend terminator, bend, or reach) of the network to the next. The type of the new network element is then determined and the appropriate processing invoked. This processing generally involves the passage of simulated time, following which the process is repeated. The processing at each type of network element is described in the following sections.

There is no central scheduling mechanism for towboats in the model. A basic assumption of the model is that a towboat of the type specified is available at the shipment segment origin port at the time the barges are available for shipment. Destinations are determined by the shipment demand.

When a tow en route to some port reaches a junction in the network, a means of determining which way to go is required. The method used by the model is based on a routing table. The routing tables are computed as part of the initialization procedure for a run. In most cases the route between a given pair of sectors is unique. This is a result of the generally tree-like structure of the waterway network; however, there may be cases where two or more routes exist between a pair of sectors. In the automatic computation of routes, this situation is resolved by selecting the route which yields the shortest distance between the midpoints of each pair of sectors.

Provision is made, however, for the model user to override the computed route choices and, if necessary, to specify the routes to be selected.

Lock Operations

(1) Basic Tow Lockage

Operations at a lock facility can be divided into two relatively independent areas: queuing, with its associated priority and chamber usage logic, and the actual passage of vessels through the lock.

When a tow arrives at a lock the first order of business is to determine whether a chamber is idle and hence available for immediate use. At a lock with more than one chamber, this also involves a decision as to which chamber should be used. The chamber which permits the tow to complete its lockage sooner is generally selected. Note that if both chambers are the same size the chamber designated as chamber 2 is considered the auxiliary chamber. This logic results in chamber 1 being the preferred one for tows of all sizes.

If a suitable chamber is available, lockage begins immediately with a fly entry. (If the last lockage in the chamber was in the same direction and insufficient time to complete a chamber turnback has elapsed, then there will be a delay before the chamber can be entered. However, this is treated as part of the lockage, which still begins immediately.) If not, the tow joins a queue of vessels waiting to use the lock. Eventually a chamber will become available and the tow will be removed from the queue to start its lockage.

The first action is to determine the type of lockage: straight single; setover (any single lockage requiring reconfiguration of the tow); or multiple-cut. The determination uses a procedure which attempts to pack the barges and towboat into the available chamber space. Since the model does not explicitly represent the configuration of barges in a tow, a random choice based on a user specified probability is used to distinguish setover from straight single lockages.

The possibility of a multiple-vessel lockage is next considered if the input option permitting them has been specified for the chamber. Multiple-tow lockages are considered only if the principle lockage type has been determined to be a straight single. In this case, the queue of vessels awaiting lockage is searched for tows which are going the same direction and can fit into the chamber with the first tow. In accordance with existing safety regulations, tows carrying hazardous cargo are not permitted to execute multiple-vessel lockages.

All information is now available to begin computation of the lockage time. At this point, the total time for approach, entry and chambering, plus turnback (if required), is calculated. The time required to reconfigure the tow for a setover or multiple cut lockage is also included in this total. Exit time cannot be determined until later because it depends on the type of exit, which in turn depends on the selection of the next vessel to use the chamber. This selection is deferred until the tow is ready to begin its exit, since the queuing situation at the lock can change during the lockage. A simulated time period during which the chamber is unavailable to other vessels now takes place, representing the approach, entry and chambering process.

Processing resumes with the start of the exit for the tow or tows in the chamber. The major task at this point is the selection of the next tow to use the chamber. This is where the chamber operating policy input parameter comes into play. If a first come-first served policy is in effect, the first tow in the queue which is able to use the chamber is chosen without regard to its direction of travel.

For a chamber operating under an N up-N down policy, the desired direction for the next lockage is first determined. The first tow in the queue traveling the desired direction and able to use the chamber is selected to use the chamber next. If no such tow can be found, then tows going the opposite direction will be considered in first come-first served order. For chambers operating under a "one-way" policy, the first tow in the preferred direction is selected. As with the N up-N down policy, if no such tow is found then tows going the opposite direction will be served.

Comparing the direction of travel of the exiting tow with that of its successor determines the exit and entry type of the corresponding tows. If both tows are traveling the same direction, a turnback exit/entry is required; opposite directions produce an exchange exit/entry. If no successor is found, the departing tow makes a fly exit. Using the exit type, the exit time for the tow in the chamber can then be computed. Meanwhile, the next tow continues to wait, its identity having been recorded.

At the end of the exit time the next tow begins its lockage and the cycle is repeated. If no next tow was found earlier, a second check of the queue is made at this time, in case another tow arrived during the exit period. If still unsuccessful, the chamber remains idle until a new arrival restarts the process. The tow or tows completing lockage advance to the next network element.

(2) Light Boats

The lockage of light boats (towboats traveling without barges) differs from that of tows in only a few respects. A separate chamber entry/exit time distribution replaces the approach, entry, and exit times applicable to tows. Light boats do not have entry or exit types associated with them. When the lockage of a tow precedes or follows one servicing only light boats the tow is considered, for the purpose of computing lockage time, to make a turn-back exit or entry regardless of the actual travel directions. This is reasonable because light boats cause negligible interference with tow approaches and exits.

(3) Recreational Traffic

The preceding discussion ignored the possibility of recreational craft at the lock, the presence of which complicates the process somewhat. Recall that recreational traffic is strictly local to each lock where its presence has been specified. Arrivals of recreational vessels are generated in a self-rescheduling manner for each lock; that is, the processing of each arrival includes the determination of the time of the next recreational arrival at the lock. Arrivals are scheduled randomly in accordance with the average arrival rates included in the input data for the lock. "Randomly" here means specifically that arrivals form a Poisson process or equivalently, that the time between arrivals is exponentially distributed. It should be noted that the primary intent of this representation is to simulate recreational use interference at the specific facility.

A separate queue is maintained for recreational vessels awaiting lockage. Recreational vessels and tows compete for lockage according to the following rules:

Tows have priority over recreational craft except as provided below.

> If a recreational vessel is forced to wait through a specified number of complete tow lockages, it is given first priority for the next lockage. (Current Corps policy sets this number at three, but it is an input parameter in the model.)
>
> Recreational vessels can lock through with non-hazardous tows if space permits. This is allowed regardless of whether multiple-tow lockages are permitted. If they are, tows have first priority at sharing the chamber, but the small size of recreational vessels obviously gives them a strong advantage in ability to utilize excess chamber

space. As with multiple-tow lockages, chamber sharing is permitted only if the main lockage is a straight single.

Recreational vessels may also obtain service in a manner not open to tows -- by locking through on a chamber turnback. Whenever an otherwise empty chamber turnback is required, recreational vessels traveling the proper direction are permitted to make their lockage with the turnback.

Like light boats, recreational vessels do not have entry, lockage or exit types associated with them and are assumed to cause negligible interference with tow approaches and exits.

A second way to simulate the effect of recreational vessels is to generate a list of arrivals exogenously and integrate them into the shipment list as a special class of traffic (using appropriate specifications of commodity class, tow type, etc.). This has the advantage of disabling the special recreational craft processing rules for situations in which they are inappropriate.

(4) Open Pass

Periods of open pass or navigable pass operations may be included for any lock by means of an input schedule which specifies the starting and ending times of each such period. In an open pass condition a lock acts as a narrow channel through which vessels may pass. A navigable pass operation occurs during periods of high water at certain locks when vessels can navigate over the dam without going through the lock chamber. In both cases, only one direction of traffic can be accommodated at a time. Not only can tows pass the lock more quickly in these states, but successive tows traveling in the same direction can follow each other closely, their passages overlapping so that the total time required is less than the summation of times of each tow taken separately.

(5) Downtime

To simulate periods when a lock chamber goes out of service due to equipment malfunctions, accidents, severe weather, scheduled maintenance, or other reasons, a list of downtime events may be input. Each record in the list specifies the location, time of occurrence, and duration of the event. When one of these events is encountered in the external events input stream, no further vessel processing occurs until after the end of the simulated downtime. If a lockage is in progress at the scheduled start of the event, the onset of the downtime is delayed until after the lockage is completed.

Bend Terminator Operations

Operations at a bend terminator can be divided into two independent areas: operations occurring when a tow arrives at a bend terminator prior to entering a bend, and operations occurring when a tow arrives at a bend terminator after having transited a bend.

(1) Effective Width of a Tow

Due to the geometry of curved bends and rectangular tows, a tow has an effective width in a bend that is greater than its actual physical width. This effective width in a bend is a function of bend radius, tow length, tow width, and direction of travel. A narrow channel is also modeled as a bend. In this case, however, the effective width of a tow is also the actual physical width of the tow. Each bend or narrow channel has a required clearance associated with it. If there is opposing traffic in a bend, the effective width of the upbound tow plus the effective width of the downbound tow plus the required clearance for the bend must be less than the width of the bend.

Bends also have a flanking length or the maximum tow length for driving through the bend. If the length of a downbound tow exceeds the flanking length, the tow will perform a flanking maneuver in order to transit the bend. In such a case, two-way traffic is not allowed while such a tow is transiting a bend.

(2) Prior to Entering a Bend

When a tow arrives at a bend terminator prior to entering a bend, a decision is made as to whether the tow may immediately enter and transit the bend or whether the tow must be queued and delayed.

(3) After Transiting a Bend

When a tow arrives at a bend terminator after having transited a bend, the queues for the bend the tow just exited are checked. If there are any downbound tows in the queue, an attempt is made to start the queued tows through the bend. If there are no downbound tows in the queue or all of the queued tows are started, an attempt is made to start any upbound tows that may be queued.

Reach Operations

The transit of a network reach, between two ports and/or locks and/or bend terminators, is represented in the simulation by an interval of simulated time. The only

processing associated with this is the computation of the tow speed and thereby the time required.

The calculation begins by determining the resistance of the tow to movement through the water. An empirical formula relating resistance to vessel dimensions determines the resistance of each barge and the towboat. Calculation of barge resistance is based on its draft, as determined by its current load. The total resistance for the tow is obtained by adding the resistances of the separate vessels and then multiplying by a factor based on the number of barges, recognizing that the total resistance is less than the sum of the individual resistances.

The tow resistance and the towboat horsepower determine, through a force equilibrium condition, the tow speed achievable in still water of unlimited depth. This speed will be reduced by restricted inland waterways, and the only one taken into account explicitly, is depth. A shallow water coefficient is computed from the depth of the channel and the draft of the tow and applied to the previously computed speed to produce the theoretical still water speed.

At this point an empirical factor specified for each reach and direction of travel is applied to take into account all the local conditions not explicitly represented in the model. Finally, the speed of the current is added or subtracted as appropriate, and the travel time is obtained from the final speed and the length of the reach.

Bend Operations

The transit of a network bend, between two bend terminators, is identical to that of the transit of a reach with two exceptions. The first exception is that tows in bends may not overtake and pass another tow traveling in the same direction. The second exception is that the computation of tow speed incorporates a flanking coefficient instead of a speed coefficient if the length of the tow is such that a flanking maneuver is required. Shorter tows will use the normal speed coefficient.

Simulation Support

The preceding sections describe the central flow of simulated operations in the model; however, as with most large simulations, a significant portion of the program is devoted to support functions. Included in this subsection are input processing, initialization of the simulated system, and output production.

(1) Input Processing

The WAM simulator requires a rather large amount of input data and a substantial portion of the program is devoted to reading the data and checking for errors. An input control routine reads the data records, produces an

echo listing if desired, determines the type of each record and invokes the appropriate routine to process the data.

An important facet of input processing is checking for errors in the data. Such problems as format errors (a non-numeric character in a numeric input field, for example), out of range errors (such as specifying a negative value for an inherently positive quantity), missing data and inconsistencies are detected and diagnosed. Errors detected in the initial input phase of model operation prevent the actual simulation from taking place; however, the program continues to read and check data.

(2) Initialization

On completion of input processing, the waterway network representation has been established and the fleet of towboats and barges defined.

In a simulation study, the analyst is generally interested in the steady state behavior of the system. (Steady state means essentially that the probability distributions of the variable describing the system, for example, the number of tows queued at a lock, are not changing with time.) Ideally, the simulated system would be initialized to a steady state condition before beginning the run. In practice this is impossible since the steady state probability distributions for the system are unknown. (If they are known, there would probably be no need to simulate the system.) To circumvent this difficulty, the standard approach of initializing the system to some convenient state, and then running the model for a "warm-up" period to bring the system approximately to steady state before starting actual collection of output statistics, is adopted.

(3) Output Preparation

This process involves the gathering of statistical data during the run and the subsequent production of output reports.

The statistics gathering function is distributed throughout the model and effectively operates in parallel with the simulated activity. The data structures representing the various components of the system include, in addition to the various descriptive attributes input for each, a number of statistical counters, accumulators and the like. For example, associated with each lock chamber are counters for the tows and barges using it and accumulators for totalling the chamber usage time. The program modules which carry out the simulation of lockage operations include program statements which correspondingly update these statistical attributes.

Preparation of reports from the accumulated statistics is a generally straightforward data processing task. One special consideration is that certain statistics need to be "closed out" before they are used. For example, the time a lock chamber is in use is normally incremented at the end of each lockage. When a chamber is in use at the end of a run, the total time does not include the total by including the time the chamber was in use for the last lockage before reporting the statistic.

A second special consideration for statistical attributes is that of resetting them, as at the end of the warm-up period. During the warm-up period no statistics actually need be gathered. Rather than treating this period as a special case and bypassing statistics collection, it is simpler to let the model run normally and then reset the counters, etc., at the end of the warm-up. Subsequent reports will reflect only the ensuing time. The mechanics of a reset operation are straightforward, most values simply being set to zero.

REFERENCES

1. U. S. Army Corps of Engineers, Pittsburgh District, *Waterway Analysis Model, Vol. II, Appendix A: User's Manual*, July 1981; draft modifications by Huntington District, January 1983.

2. Bronzini, M. S., et al., *Inland Waterway Systems Analysis, Vol. V, Waterway Analysis*, CACI, Inc., Arlington, VA, for U.S. Army Corps of Engineers, Washington, D.C., July 1976.

GLOSSARY

Definitions of many of the technical terms used in this report are given in this appendix. For the most part these are terms relating to shallow draft navigation in the U.S., and these definitions are provided mainly for the convenience of readers who may not have encountered them previously. This information has been taken from a previous report prepared for the Corps of Engineers.

approach	Travel of a tow from the approach point, or from a point on the lock guidewall clear of the lock gates in the case of a turnback approach, to a point where the bow of the tow is abreast of the lock gates and the tow is parallel to the guidewall ready to enter the lock chamber.
approach point	The closest point to a lock at which one tow can safely pass another tow traveling in the opposite direction. Tows may not normally proceed beyond the designated approach point of a lock without the permission of the lockmaster.
auxiliary chamber	A chamber of a multiple-chamber lock which is usually smaller and used less than the main chamber. Auxiliary chambers are normally used to pass small tows, light boats, and recreational vessels, and to maintain navigation during periods when the main chamber is shut down.
chambering	That part of a lockage cycle starting at the end of the entry and ending when the exit gates are fully recessed, or when the bow of the exiting vessel crosses the lock sill, whichever is earlier. Chambering includes closing the entry gates, filling or emptying the lock chamber, and opening the exit gates.
cut	A segment of a tow which is put through a lock separately from other segments of the tow
delay time	The time elapsed from the arrival of a vessel at a lock to the start of its approach to a lock chamber; the time spent in queue awaiting lockage.
double lockage	The type of lockage performed when a tow is passed through a lock chamber in two segments or "cuts".

entry	That part of a lockage cycle starting at the end of the approach and ending when the tow or cut is secured within the chamber and the gates are clear, or when the closing of the gates has been initiated, whichever is earlier.
exchange approach	The type of approach executed when the vessel inbound to the chamber passes a vessel outbound from the chamber.
exchange exit	The type of exit executed when the vessel outbound from the chamber passes a vessel inbound to the chamber.
exit	That part of a lockage cycle starting at the end of chambering and ending when the lock has completed serving a vessel or cut and can be dedicated to another vessel or cut.
fly approach	The type of approach executed when the lock has been idle and the inbound vessel proceeds directly to the chamber.
fly exit	The type of exit executed when the lock will be idle following the departure of the outbound vessel, that is, when no vessels are awaiting lockage.
lockage time	The time elapsed from the start of approach of the first vessel or cut served by a lockage to the end of exit of the last vessel or cut served by a lockage. Includes the time required to disassemble and assemble multiple-cut tows and to rearrange setover tows, when such activities prevent the use of the lock by other vessels.
multiple-cut lockage	The type of lockage performed when a tow must be passed through the lock in two or more segments or "cuts".
multiple-vessel lockage	A type of lockage in which more than one vessel or tow is served in a single lockage cycle.
open pass	Passage of a vessel through a lock with no lock hardware operation. This is possible only when the upper and lower pool levels are nearly equal, and occurs most frequently at tidal locks.
pool	The body of water impounded by a navigation dam.

setover lockage	A lockage in which the towboat and one or more barges are separated as a unit from the remaining barges and set alongside of them in the lock chamber. The term is usually applied only to single lockages, but it could be used to describe any cut. The term is often used to refer to all types of single lockages requiring rearrangement of the tow.
single lockage	The type of lockage performed when the entire tow can fit into the lock chamber, with or without rearrangement, and hence requiring only one lock operating cycle.
straight lockage	A lockage which does not require rearrangement of the tow in order for the tow to fit into the lock chamber. The term is usually applied only to single lockages, but it could be used to describe any cut.
turnback	A lockage in which no vessels are served; a reversal of the water level in a lock chamber with no vessels in the chamber. A turnback includes closing one set of gates, filling or emptying the chamber, and opening the other set of gates. Also called a "swingaround" or an "empty lockage".
turnback approach	The type of approach executed when the preceding event at the lock was a chamber turnback.
turnback exit	The type of exit executed when the next event is a lockage in the same direction, requiring a chamber turnback.

APPENDIX E

SIMULATION OF CONCEPTUAL ALTERNATIVES

NOTE:

Appendix E was prepared during Phase 1.
If there are any conflicts between the data in this appendix and data in the body of the report, the data in the report proper governs.

APPENDIX E
SIMULATION OF CONCEPTUAL ALTERNATIVES

This chapter presents the data, methods, and assumptions used to structure the inputs to the Waterway Analysis Model (WAM) for simulating the baseline and alternative configurations of the Panama Canal. Model calibration is considered first, followed by a discussion of the inputs for each of the alternative conceptual plans.

The inputs to the model are extensive, rendering it impractical to provide tables with all of the data within the covers of this report. These data files are available on DOS-compatible diskettes.

MODEL CALIBRATION

The basic WAM inputs are a network file, a downtime file, and a ship list file. The network file contains the bulk of the information on the waterway being studied, and is described next, followed by sections on the other inputs. The results of model calibration runs for the base year of 1990 are then presented.

Network Data

(1) Network Structure

A basic node and link file describing the present layout of the Panama Canal was prepared by the Corps of Engineers. Figure E-1 is a schematic diagram of this basic layout. Some minor changes were made to conform to various model requirements, but Figure E-1 shows all of the primary features of interest. Many model inputs must be specified according to the upstream or downstream travel directions. To accommodate this, the Atlantic Ocean end of the system was arbitrarily designated as the upper end, with milepoint 0.0. Thus, in the model inputs and outputs "Upstream" corresponds with northbound and "Downstream" with southbound. All points are located by milepoint, and all linear distances are recorded and computed using statute miles as the unit of measure. Lock, channel, and vessel dimensions use feet as the basic unit.

As shown, the network structure consists of ports, locks, channels (including lakes), and bends, which are restricted channel segments. The network structure is a general purpose one, so various input parameters were selected to tailor it to the precise purposes of the Phase 1 simulation runs. For example, the bends in Gatun Lake do not impose any appreciable restrictions on navigation, so their geometric and operational parameters were selected to permit unimpeded passage of vessels. Likewise, port operations are not of interest in this study, so all port variables were set so as to render the model's port loading, unloading, and dispatching logic inoperable.

SCHEMATIC OF BASIC NETWORK FOR WAM

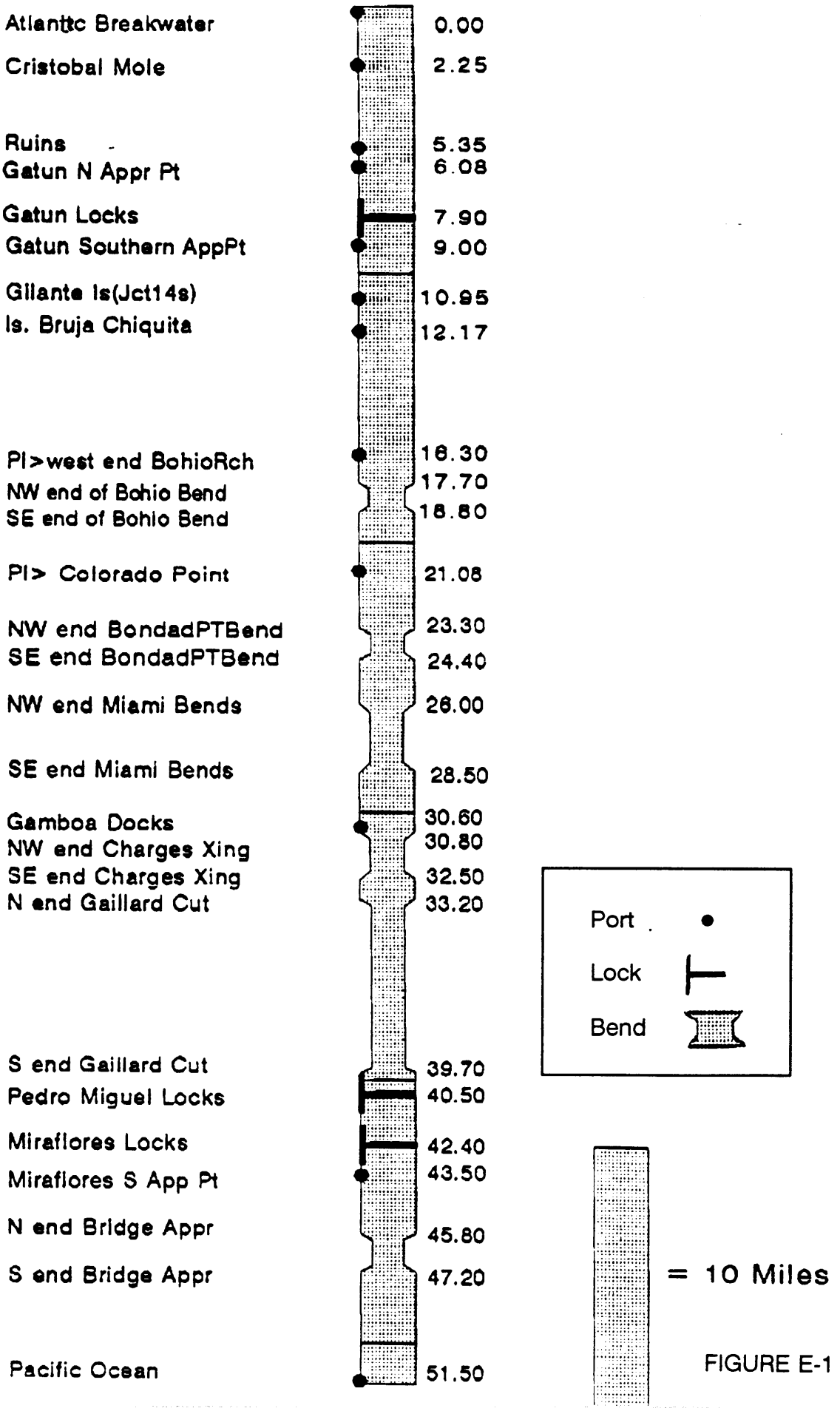

FIGURE E-1

The bendway representing the Gaillard Cut deserves special mention. It was input as a single straight channel segment, with a width of 500 feet and with vessel clearance requirements such that two vessels with combined beam exceeding 140 feet would not be allowed to pass. The basic effect for these WAM runs is that class 6 vessels and larger, which have beams greater than or equal to 95 feet, would require a clear cut. The more detailed geometry of the Cut was not represented, since it would have no added impact on vessel operations in the model.

(2) Locking Times

All of the locking time data were utilized to estimate locking time distributions for input to the model. Heavy reliance was placed on the Ship Data Bank records.

The WAM locking time input data comprises separate statistical distributions for approach, entry, chambering, and exit times for each vessel class by direction, plus a few miscellaneous time components. The data required are a bit more detailed than what is available from the SDB. A principal difficulty is that the SDB records combine entry, chambering, and exit time into one composite time, which was defined as "lockage time." A second difficulty is that delay time is not separated from operational time. A third problem is that no data are kept on the specifics of a lockage, such as which lane was used, whether relay operations were in effect, double versus single culvert, and so on. Thus, the supplemental data collected on site plus the judgement of staff experienced in lock simulation were needed in order to distill a usable WAM data set from the available source data.

The following steps were followed to estimate the input locking times:

1. Average values for entry and exit times were estimated based on the locking times observed during data collection on-site in Panama. These were input as constants.

2. Mean chambering time was computed as (locking time - entry time - exit time), and minimum chambering time was similarly computed. The standard deviation of chambering time is identical to that for locking time, since the two distributions differ only by a constant.

3. The mean, standard deviation, and minimum approach times were used as given, with no changes.

4. The parameters for approach and chambering times were modified to provide a smooth relationship and consistent progression going across the vessel classes from the smaller ships up to the Panamax vessels.

5. The approach and chambering times were represented as Gamma or Weibull distributions. Parameters were estimated to approximate the

means, standard deviations, and locations (i.e., minimum values) computed as described above, and to provide shapes that are consistent with the field observations and with engineering judgement.

6. The approach times were input as the "fly/exchange" approach times used in the model, which apply to consecutive opposite direction lockages in the same lane. Turnback approach times, which apply to consecutive same direction lockages in a lane, were set at about 75 percent of the fly/exchange times.

7. Based on field observations, the extra time for a tandem lockage was set at a constant 5 minutes for all locks. Also, chamber turnback time, which is the maximum time interval between successive same direction lockages in one lane and which is made up primarily of locomotive travel time, was set at 5, 10, and 15 minutes for Pedro Miguel, Miraflores, and Gatun locks, respectively.

8. An initial calibration run for 1990 was made, and the resulting average lockage times by vessel class were compared with the PCC schedule times for regular lockage. Recognizing that the latter times include some allowance for delays and are based on double culvert operations, the input distributions for chambering times were altered to produce a closer match. This required reducing the locking times for the smaller vessels and increasing it for the larger vessels. A subsequent calibration run was judged to produce acceptable results. Final values for the locking time input distributions are given in Tables E-1 through E-3.

9. To develop distributions for relay lockages at Gatun and Miraflores, the turnback approach times were reduced by approximately 5 minutes, and the chamber turnback times were set to zero. The exact times used are given in Table E-4.

(3) Vessel Characteristics

The ship characteristics determined from the SDB records, served as the starting point. Vessel block coefficients and minimum depths were selected to produce correct length-width-draft-displacement relationships. All resulting values were smoothed across vessel classes to produce the final WAM input (Table E-5). The model results are not overly sensitive to the vessel characteristics, so this procedure is judged to be acceptable for Phase 1. Consideration will be given to modifying the dimensions for Phase 2, in light of the experience gained in Phase 1.

The principal use of the vessel dimensions and horsepower is to compute vessel speed in channels and bendways, using the WAM speed function. Based on preliminary calibration run results, channel and bendway speed coefficients were

selected to produce average output speeds that are in reasonable agreement with observed data and with the PCC vessel scheduling times. Typical coefficient values, which are applied as multipliers of the speed function result, are 0.75 for the channels and 0.50 for the bendways. The fact that an across the board adjustment could be used indicates that the speed function and vessel characteristics are doing a good job of computing relative vessel speeds.

Lock Downtime Data

The Locks Delay Data Base provided by the PCC listed all random delay events recorded in 1990, by lock, day of occurrence, type of event, and duration. The events were not separated by lane, nor was the time of occurrence recorded. Analysis of these data indicated that the frequency and duration of the delay events varied by lock, but not by day of week or month. Consequently the data were pooled for each lock for further analysis.

The downtime event data file for input to the model must specify the time of occurrence, lock, lane, and duration. For each lock, the downtime events for 1990 were sorted by day of year. Then, within each day each event was assigned a random start time, and randomly assigned to one of the lanes. Also, a downtime of eight hours duration was scheduled at lane two of Pedro Miguel locks at midnight of each day, to model the nightly reversion to single-lane operations. The scheduled lane outages reported by the PCC for 1990 were added to the file. These included two 11½ day outages of one lane for gate replacement at Gatun, some multiple day outages at the other locks, and monthly eight-hour lane outages for preventive maintenance. The resulting composite downtime file was modified to remove overlapping events at a single lane, simultaneous scheduled shutdowns of both lanes at a lock, and other inconsistencies.

Ship List

Development of the 1990 ship list from the full set of SDB records was described previously in this report. The actual recorded ship underway time was used as the time that the vessel is assumed to begin its transit, thereby incorporating any schedule delays imposed on the vessel but keeping the associated delay time outside of the simulation. Computation of the difference between underway time and ready time for the entire ship list revealed that the average such delay was 11.6 hours, with a standard deviation of 13.0 hours and a maximum of 106.5 hours (the minimum value was zero, as expected). It is believed that this large number is due, in part, to restriction in night time transit of large ships through the Gaillard Cut. With the elimination of this restriction in the future, this delay time should be reduced substantially.

Calibration Results

The lack of a data set that separates travel time, locking time, and delay time limits what can be done to quantitatively assess the absolute level of accuracy of the WAM results. The best that can be done is to compare the results to the SDB data used to derive the inputs, and to the PCC schedule times.

Table E-6 shows the WAM average locking time outputs and the PCC lockage schedule times. The overall level of agreement is within acceptable limits for Phase 1. For the regular lockage case, the agreement is particularly good at Pedro Miguel and Miraflores, and through vessel class 9 at Gatun. In general, simulated average locking time is lower than the schedule time for the smaller vessel classes, and larger for classes 8 through 12. This is somewhat in line with expectations. The schedule includes some delay allowance, so one would expect a lower simulated lockage time, which excludes delay time. On the other hand, the schedule for the larger vessels seems to exclude the rather long locking times that are observed to occur for these classes.

It is apparent that the scheduled times for relay lockage assume that ships are locking consecutively, and thus full credit for zero locomotive travel time is taken. In the model, the turnback time is not counted as part of a vessel's locking time. Consequently, to obtain comparable figures, the average locking times output in the calibration run with relay lockage were reduced by 10 and 15 minutes at Miraflores and Gatun, respectively. The simulated relay lockage times appear to be a bit high as compared with the schedule times, especially for the larger vessels. However, there is no reason to suspect that the relay lockage times should differ from the regular times by more than the savings in locomotive travel time plus a small savings in approach time, as assumed in preparing the model input. Also, the schedule times for large vessels are too low to begin with, as noted above for the regular lockages. Thus, the results for the relay lockage case are also judged to be acceptable for Phase 1.

Table E-7 displays the locking times output by WAM along with the values obtained from the SDB records (sum of approach and lockage). Recognizing that the SDB values listed are taken from the unsmoothed data and include some delay time, the agreement is reasonable. The standard deviations in the WAM results tend to be smaller than the SDB standard deviations, indicating that the analytical intent to use somewhat more compact distributions than those of the raw data was achieved.

The average lock delays recorded in the calibration run (regular lockage) are as follows:

	Average Delay (hour)	Lock Utilization (percent)
Gatun	3.1	75
Pedro Miguel	0.3	43
Miraflores	0.2	58

The higher delay at Gatun is a reflection of both the higher service time and the two 11½ day lane outages. The results appear to be reasonable. As noted earlier, the average vessel speeds in the WAM output also agree reasonably well with observed data.

The overall average ship transit times (hours) in this run are as follows:

	North	South	Average
Travel	7.51	7.71	7.66
Delay	4.55	3.67	4.06
Total	12.06	11.38	11.72
SDB Data	12.5	9.8	11.1

As indicated, the match with the transit time results from analysis of the SDB records is relatively good. Combining this with the average of 11.6 hours of schedule delay experienced in 1990 indicates that the simulated time in canal waters is about 22.7 hours, which is under the PCC standard of 24 hours by only a small margin. This matches the information obtained during the visits of the research team to Panama.

In summary, the model calibration was deemed to be good enough to proceed with the simulation of the alternative conceptual plans. In particular, the results are sufficiently accurate to permit a screening level comparison of the plans. In Phase 2 a tighter calibration will be attained, in order to permit more confidence in the model's absolute results.

ALTERNATIVE SYSTEMS

Data and assumptions used to prepare WAM inputs for simulation of the alternative conceptual plans are documented in this section. Development of the ship lists is covered first, followed by information on preparation of the network and downtime files.

It should be noted that all of the conceptual plans which include multiple lift locks were simulated assuming continuous relay operations. The rationale for this is that this type of operation determines the ultimate capacity of any system configuration.

In reality, relay operations would be scheduled on an as needed basis to provide the needed level of service to vessel operators.

Ship Lists

The ship types used in the WEFA traffic forecasts were mapped into the 14 vessel classes defined for the WAM runs, as shown in Table E-8. The basic criterion for the mapping was to obtain a match on ship displacement. As long as a reasonable match is made, the model results are not overly sensitive to this assumption; that is, assigning a WEFA ship type to class 3 rather than class 2 will have little or no effect on the model results. Table E-8 applies to the 65,000 DWT design ship case for the year 2020. A few entries were modified for other cases where the average ship displacement was expected to increase, but this matrix remained substantially the same throughout the analysis. In addition, the WEFA ship type was retained on the ship list as the commodity code (CB = commodity 1, F = commodity 2, etc.), so future revisions of the ship class assignments are possible without the necessity of regenerating the ship list.

Eight new vessel classes were defined to accommodate the larger design ship types, as follows:

Vessel Class	Description
15	100,000 DWT ship, ballast
16	100,000 DWT ship, laden
17	150,000 DWT ship, ballast
18	150,000 DWT ship, laden
19	250,000 DWT ship, ballast
20	250,000 DWT ship, laden
21	300,000 DWT ship, ballast
22	300,000 DWT ship, laden

Vessel characteristics were set according to the specified design ship dimensions, and to have them fit smoothly into the family of ship classes defined previously.

Analysis of the distribution of time gaps between successive vessel ready to transit times in the SDB records showed that these follow a negative exponential probability distribution, indicating that future vessel underway times could be generated as a Poisson process. Accordingly, a ship list was generated for each WEFA ship transit forecast by preparing a ship list record for each ship in the forecast, randomly ordering these records, then randomly assigning the ship underway times by drawing from a negative exponential distribution with a mean equal to 365 days divided by the total number of ships. Scheduling the large ships to avoid night operations in the Gaillard Cut was not necessary, since a basic assumption of the analysis is that the Cut would be widened sufficiently to no longer be a constraint on system operations.

Status Quo

The status quo conceptual plan is nearly identical to the system defined for the 1990 calibration runs. The principal change is that the bendway representing the Gaillard Cut was modified to eliminate all clear cut and night time restrictions. This is the type of operation that will be gradually introduced by the PCC, on an as needed basis, after the widened Cut is available. It is assumed that transition to full implementation would occur by the year 2020, and that the Cut would no longer be a determinant of system capacity.

The lock downtime files were modified to remove the nightly shutdown of one lane at Pedro Miguel, in order to avoid having this become a capacity constraining operation. In reality, the present mode of operation might well persist if it continues to provide sufficient capacity. The special maintenance outages that occurred in 1990, such as the Gatun gate replacement, were also removed from the file.

High-Rise Locks

The network description for this plan was developed by modifying the status quo network file to add new channels for the third locks. All existing and new channels that would be traversed by the larger ships were modified to provide the minimum design depth (channel width is not a factor in the WAM speed function), and new locks with the dimensions indicated below were added in the new channels:

	100,000 DWT	150,000 DWT	250,000 DWT
New Locks (ft)	1,046 x 154	1,191 x 177	1,220 x 187
Min. Channel Depth (ft)	62	69	79

Again, it was assumed that the Gaillard Cut channel dimensions would be consistent with those at other reaches, so that the existing night time and clear cut restrictions would not apply.

Locking times at the new Atlantic lock (Table E-9) were based upon the locking times estimated for the existing Miraflores Locks for most existing ship sizes, since the new lock would have only two lifts. The largest ships to use the new lock for any design ship case were assigned locking cycle times ranging from 93 to 117 minutes, which agree with the Y.E.C. design analysis and also provide a smooth fit with the Miraflores data. As the design ship became larger, the times for the vessel classes between class 15 and the design ship were reduced, to account for operations in a larger chamber and to provide a smooth progression of times throughout the distribution. The locking times at the new Pacific lock (Table E-10) were set 10 minutes lower, again reflecting the Y.E.C. design analysis. The exact times used for all of these cases may be inspected in the WAM input or output files for each case.

The downtimes for the existing Miraflores Locks were assumed to apply to the new locks.

Single-Lift High-Rise Canal

This system was modeled with a lake level of 85 feet and a single-lift in the new locks, for only the 100,000 DWT design ship case. The network inputs were identical to the high-rise canal system, except as follows:

1. Minimum and average channel depths were changed to reflect the five-foot reduction in the level of Gatun Lake.

2. Locking times at the third locks were reduced by the sum of Entry Time + Exit Time + 2 minutes, for each vessel class, to simulate single-lift operation.

Low-Rise Canal

This system was modeled with a lake level of 55 feet, and with a single-lift at the third locks. Accordingly, locking times at these facilities were reduced as compared with the high-rise system. Channel minimum and average depths were modified to account for the lower lake level, but to still provide the required minimum depths. The new lake level is at the lower level of Pedro Miguel Locks, so this facility was removed from the network. Similarly, the upper level at Gatun would no longer be functional, so locking times were reduced to reflect two lift operation. The lock downtimes for the high-rise system were assumed to apply to this plan as well.

Sea-Level Canal

The sea-level canal was modeled as a separate system, not connected to the existing canal. The Route 10 case was assumed, with a 58 km cut across the Isthmus and double lane approaches for a total length of channel ranging from 87 to 90 km. The 58 km cut was assumed to be alternatively single-lane, dual-lane, or partial single and partial dual lane. Positive tidal current control was assumed to be provided by tide gates spaced at either 58 or 40 km, with one gate always at the Pacific end, or by tidal locks at the Pacific side of the cut.

Tide gates were simulated as locks, with all locking time components set to zero except chambering times for ships entering the canal section, which were set at values corresponding to the minimum safe ship separation times. Based upon the experience in running convoys through the Suez Canal and general confirmation by our navigation consultant, times ranging from 6 minutes for the smaller vessels up to 27 minutes for the larger vessels were used. The WAM output for these systems shows that the minimum ship spacing averaged over all vessel classes was about 15 minutes. The actual average spacing is larger by a small but

unknown amount, since any time gaps between consecutive vessels caused by the randomness in the vessel arrival pattern are not captured in the model output. In general, systems operating in the regime near capacity will have average vessel spacings that are very close to this 15 minute average.

The canal section was modeled as a restricted straight channel section, using the WAM bendway feature, as was the case with the Gaillard Cut. Again, the model results are not sensitive to the precise geometry of the canal section. Channel and bendway speed coefficients were input so as to obtain the desired average vessel speed. For the cases with a single-lane canal, cycle times were imposed through the use of the lock downtime feature. A lock (simulating a tide gate) is open to entering traffic for approximately one-half of the cycle time, and then is closed to traffic from the same direction for one and one-half cycles while the convoy exits and an opposite direction convoy uses the canal. For the single-lane canal with Pacific locks, a "phantom" lock was introduced at the Atlantic end to provide a mechanism for simulating convoy formation and minimum ship spacing.

The Pacific Locks were modeled with locking times selected to produce an average service rate of three ships per hour per canal lane (equivalent to three parallel locks per lane). Downtimes beyond those needed for single-lane convoy operations were borrowed from the downtime files for the existing Pedro Miguel and Miraflores locks.

Combined Systems

Model input files combining the single-lane sea-level canal plans with the status quo system were also prepared, to obtain capacity estimates for these combined systems. Combined systems with tide gates were simulated using the ship lists for the 150,000 DWT and 250,000 DWT design ship cases, while the single lane with locks system was run in combination with the status quo system only for the 250,000 DWT case as requested by CAS. All input data and assumptions for the individual systems were carried over directly to the input files for the combined systems.

Simulation Run Procedures

All WAM runs were configured to simulate one entire year of operation, so as to process all of the ships on the ship list. In view of this long simulation period and the relatively short time required to transit the canal, no simulation warm-up period was used. That is, each run started with the system empty and awaiting the transit of the first vessel on the ship list. Examination of trial runs of different length (eg., 5 days, 60 days, 365 days) indicated that this end effect was unimportant.

The question of which classes of ships to route through the new channels for the third locks and combined sea-level and status quo systems was resolved in the following manner. For the high-rise and low-rise canal plans, ship classes 1

through 11 and class 13 were routed initially through the existing locks, and all larger vessels were routed through the new locks. Subsequently, one-quarter of the class 12 vessels were routed through the existing locks, in order to achieve a better balance in delay times between the new and existing locks, thus obtaining a higher overall capacity. For the combined systems the initial routing strategy proved to be acceptable, so all of the class 12 vessels use the sea-level canal in these runs.

These provisions for use of relay lockage and for assigning ships to alternative channels are temporary modeling procedures adopted for Phase 1 of the study. The Phase 2 version of the model will permit dynamic selection of locking method and route assignment, based upon the simulated traffic and delay conditions.

For nearly all of the cases simulated, runs were made using the year 2020 and 2060 ship lists, in order to obtain two points on the system delay curve. The exceptions to this general rule are as follows:

1. The status quo system reaches capacity well before year 2060. Consequently, a run was made with 63% of 2020 traffic, in order to provide a data point on the lower arm of the delay curve.

2. Sea-level canal systems with a single lane have a capacity that is very near the 2020 traffic level. In addition, due to the fixed operating cycle three data points are needed to estimate the delay curve. For these cases, runs were made at three traffic levels selected from 33%, 50%, 80%, and 100% of the year 2020 traffic.

A total of 42 simulations were run.

From a theoretical perspective, many analysts would prefer to produce two delay curves for each conceptual alternative, based on four model runs rather than only two runs. The first curve would be for the ship mix represented in the year 2020 ship list, and would be derived from model runs made with the traffic levels forecast for 2020 and 2060. The second curve would be based on the year 2060 ship mix, again for the 2020 and 2060 traffic levels. The advantage of this approach is that it separates the effects of changing traffic levels and changing vessel characteristics. The disadvantages, besides requiring twice as many simulation runs, are that this procedure requires the analyst to imagine the path of transition from the first curve to the second. The simpler procedure used in this study has been found to work well in practice, and is judged to be adequate for the prescreening process.

Another factor not modeled in Phase 1 is the possible occurrence of delays where vessels must cross paths or merge with other vessels at the locations where the proposed new channels intersect the existing channels. In general, the effective time of a vessel meeting or merging maneuver is much less than the lock service

times that serve to meter traffic into the channels, and is also less than the average vessel interarrival times simulated. Further, at very heavy traffic levels it is likely that at least one of the vessels subject to a crossing delay is traveling toward a queue, and could incur some crossing delay without actually increasing its total transit time. For these reasons, it is reasonable to ignore this possible source of delay for the prescreening.

SIMULATION RESULTS

The output files produced by the WAM runs, including the printout file and the ship resource file, are available on discs. The manner of analyzing these results, and the delay curves and capacity estimates for the alternative conceptual plans are presented in the next chapter.

TABLE E-1
LOCKING TIME INPUT DATA; GATUN LOCKS, REGULAR LOCKAGE

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
1	Approach, Fly/Exchange	G	16.0	1.0	2.0	G	11.0	1.0	2.0
	Approach, Turnback	G	12.0	1.0	2.0	G	8.3	1.0	2.0
	Entry	K	3.0			K	3.0		
	Chambering	W	2.0	20.3	11.0	G	28.0	4.5	10.0
	Exit	K	4.0			K	4.0		
2	Approach, Fly/Exchange	G	16.0	1.0	2.0	G	11.0	1.0	2.0
	Approach, Turnback	G	12.0	1.0	2.0	G	8.3	1.0	2.0
	Entry	K	3.0			K	3.0		
	Chambering	W	2.0	20.3	11.0	G	28.0	4.5	10.0
	Exit	K	4.0			K	4.0		
3	Approach, Fly/Exchange	G	16.0	1.0	2.0	G	11.0	1.0	2.0
	Approach, Turnback	G	12.0	1.0	2.0	G	8.3	1.0	2.0
	Entry	K	3.0			K	3.0		
	Chambering	W	2.0	20.3	11.0	G	28.0	4.5	10.0
	Exit	K	4.0			K	4.0		
4	Approach, Fly/Exchange	G	18.0	1.0	3.0	G	13.0	1.0	3.0
	Approach, Turnback	G	13.5	1.0	2.0	G	9.8	1.0	2.0
	Entry	K	5.0			K	5.0		
	Chambering	W	2.0	20.3	22.0	G	38.0	4.5	20.0
	Exit	K	5.0			K	5.0		

Table E-1 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
5	Approach, Fly/Exchange	G	18.0	1.0	3.0	G	13.0	1.0	3.0
	Approach, Turnback	G	13.5	1.0	2.0	G	9.8	1.0	2.0
	Entry	K	5.0			K	5.0		
	Chambering	W	2.0	20.3	22.0	G	38.0	4.5	20.0
	Exit	K	5.0			K	5.0		
6	Approach, Fly/Exchange	G	21.0	1.0	3.0	G	16.0	1.0	3.0
	Approach, Turnback	G	15.8	1.0	2.0	G	12.0	1.0	2.0
	Entry	K	6.0			K	6.0		
	Chambering	W	2.0	20.3	22.0	G	38.0	4.5	20.0
	Exit	K	6.0			K	6.0		
7	Approach, Fly/Exchange	G	21.0	1.0	3.0	G	16.0	1.0	3.0
	Approach, Turnback	G	15.8	1.0	2.0	G	12.0	1.0	2.0
	Entry	K	6.0			K	6.0		
	Chambering	W	2.0	20.3	22.0	G	42.0	4.5	24.0
	Exit	K	6.0			K	6.0		
8	Approach, Fly/Exchange	G	21.0	1.0	3.0	G	16.0	1.0	3.0
	Approach, Turnback	G	15.8	1.0	2.0	G	12.0	1.0	2.0
	Entry	K	6.0			K	6.0		
	Chambering	W	2.0	20.3	40.0	W	2.0	24.8	37.0
	Exit	K	6.0			K	6.0		

Table E-1 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
9	Approach, Fly/Exchange	G	23.0	1.2	4.0	G	17.0	1.0	4.0
	Approach, Turnback	G	17.3	1.2	3.0	G	12.8	1.0	3.0
	Entry	K	7.0			K	7.0		
	Chambering	W	2.0	20.3	19.0	G	37.0	2.7	19.0
	Exit	K	6.0			K	6.0		
10	Approach, Fly/Exchange	G	23.0	1.2	4.0	G	17.0	1.0	4.0
	Approach, Turnback	G	17.3	1.2	3.0	G	12.8	1.0	3.0
	Entry	K	7.0			K	7.0		
	Chambering	W	2.0	22.6	40.0	W	2.0	24.8	37.0
	Exit	K	6.0			K	6.0		
11	Approach, Fly/Exchange	G	23.0	1.1	5.0	G	18.0	1.0	5.0
	Approach, Turnback	G	17.3	1.1	4.0	G	13.5	1.0	4.0
	Entry	K	10.0			K	10.0		
	Chambering	W	2.0	22.6	61.0	W	2.0	27.1	54.0
	Exit	K	7.0			K	7.0		
12	Approach, Fly/Exchange	G	23.0	1.1	5.0	G	18.0	1.0	5.0
	Approach, Turnback	G	17.3	1.1	4.0	G	13.5	1.0	4.0
	Entry	K	10.0			K	10.0		
	Chambering	W	2.0	31.6	77.0	W	2.0	31.6	86.0
	Exit	K	7.0			K	7.0		

Table E-1 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
13	Approach, Fly/Exchange	G	18.0	1.0	3.0	G	13.0	1.0	3.0
	Approach Turnback	G	13.5	1.0	2.0	G	9.8	1.0	2.0
	Entry	K	5.0			K	5.0		
	Chambering	W	2.0	20.3	22.0	G	38.0	4.5	20.0
	Exit	K	5.0			K	5.0		
14	Approach, Fly/Exchange	G	16.0	1.0	2.0	G	11.0	1.0	2.0
	Approach, Turnback	G	12.0	1.0	2.0	G	8.3	1.0	2.0
	Entry	K	3.0			K	3.0		
	Chambering	W	2.0	20.3	15.0	W	2.0	20.3	15.0
	Exit	K	4.0			K	4.0		
All	Chamber Turnback	K	15.0			K	15.0		
	Tandem Extra	K	5.0			K	5.0		

Type Codes: G = Gamma K = Constant W = Weibull
Pn = Parameter n (See Appendix G)
All numerical values are minutes.

TABLE E-2
LOCKING TIME INPUT DATA; MIRAFLORES LOCKS, REGULAR LOCKAGE

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
1	Approach, Fly/Exchange	G	8.0	1.0	2.0	G	9.5	1.0	2.0
	Approach, Turnback	G	6.0	1.0	2.0	G	7.1	1.0	2.0
	Entry	K	4.0			K	4.0		
	Chambering	G	18.0	1.8	10.0	G	17.0	2.0	10.0
	Exit	K	4.0			K	4.0		
2	Approach, Fly/Exchange	G	8.0	1.0	2.0	G	9.5	1.0	2.0
	Approach, Turnback	G	6.0	1.0	2.0	G	7.1	1.0	2.0
	Entry	K	4.0			K	4.0		
	Chambering	G	18.0	1.8	10.0	G	17.0	2.0	10.0
	Exit	K	4.0			K	4.0		
3	Approach, Fly/Exchange	G	8.0	1.0	2.0	G	9.5	1.0	2.0
	Approach, Turnback	G	6.0	1.0	2.0	G	7.1	1.0	2.0
	Entry	K	4.0			K	4.0		
	Chambering	G	23.0	1.8	15.0	G	22.0	2.0	15.0
	Exit	K	4.0			K	4.0		
4	Approach, Fly/Exchange	G	9.5	1.0	3.0	G	11.0	1.0	3.0
	Approach, Turnback	G	13.5	1.0	2.0	G	9.8	1.0	2.0
	Entry	K	5.0			K	5.0		
	Chambering	G	28.0	2.1	20.0	G	27.0	1.6	20.0
	Exit	K	5.0			K	5.0		

Table E-2 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
5	Approach, Fly/Exchange	G	9.5	1.0	3.0	G	11.0	1.0	3.0
	Approach, Turnback	G	7.1	1.0	2.0	G	9.8	1.0	2.0
	Entry	K	5.0			K	5.0		
	Chambering	G	28.0	2.1	20.0	G	27.0	1.6	20.0
	Exit	K	5.0			K	5.0		
6	Approach, Fly/Exchange	G	11.2	1.0	4.0	G	14.5	1.0	4.0
	Approach, Turnback	G	8.4	1.0	3.0	G	10.9	1.0	3.0
	Entry	K	6.0			K	6.0		
	Chambering	G	28.0	2.1	20.0	G	27.0	1.4	20.0
	Exit	K	5.0			K	5.0		
7	Approach, Fly/Exchange	G	11.2	1.0	4.0	G	14.5	1.0	4.0
	Approach, Turnback	G	8.4	1.0	3.0	G	10.9.0	1.0	3.0
	Entry	K	6.0			K	6.0		
	Chambering	W	2.0	11.3	26.0	G	34.0	1.8	26.0
	Exit	K	5.0			K	5.0		
8	Approach, Fly/Exchange	G	11.2	1.0	4.0	G	14.5	1.0	4.0
	Approach, Turnback	G	8.4	1.0	3.0	G	10.9	1.0	3.0
	Entry	K	6.0			K	6.0		
	Chambering	W	2.0	14.7	32.0	W	2.0	12.4	32.0
	Exit	K	5.0			K	5.0		

Table E-2 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
9	Approach, Fly/Exchange	G	13.3	1.8	4.0	G	16.3	1.0	4.0
	Approach, Turnback	G	10.0	1.8	3.0	G	12.2	1.0	3.0
	Entry	K	7.0			K	7.0		
	Chambering	W	2.0	12.4	25.0	G	33.0	1.8	25.0
	Exit	K	5.0			K	5.0		
10	Approach, Fly/Exchange	G	13.3	1.8	4.0	G	16.3.0	1.0	4.0
	Approach, Turnback	G	10.0	1.8	3.0	G	12.2	1.0	3.0
	Entry	K	7.0			K	7.0		
	Chambering	W	2.0	17.0	31.0	G	43.0	2.5	32.0
	Exit	K	5.0			K	5.0		
11	Approach, Fly/Exchange	G	14.3	2.2	4.0	G	16.3	1.0	4.0
	Approach, Turnback	G	10.7	2.2	3.0	G	12.2	1.0	3.0
	Entry	K	8.0			K	8.0		
	Chambering	G	56.0	3.0	42.0	G	52.0	2.9	40.0
	Exit	K	6.0			K	6.0		
12	Approach, Fly/Exchange	G	14.3	2.2	4.0	G	16.3	1.0	4.0
	Approach, Turnback	G	10.7	2.2	3.0	G	12.2	1.0	3.0
	Entry	K	8.0			K	8.0		
	Chambering	W	2.0	19.2	52.0	W	2.0	20.3	44.0
	Exit	K	6.0			K	6.0		

Table E-2 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
13	Approach, Fly/Exchange	G	9.5	1.0	3.0	G	11.0	1.0	3.0
	Approach Turnback	G	7.1	1.0	2.0	G	8.3	1.0	2.0
	Entry	K	5.0			K	5.0		
	Chambering	G	28.0	2.1	20.0	G	27.0	1.6	20.0
	Exit	K	5.0			K	5.0		
14	Approach, Fly/Exchange	G	8.0	1.0	2.0	G	9.5	1.0	2.0
	Approach, Turnback	G	6.0	1.0	2.0	G	7.1	1.0	2.0
	Entry	K	4.0			K	4.0		
	Chambering	G	21.0	2.2	7.0	G	21.0	2.2	7.0
	Exit	K	4.0			K	4.0		
All	Chamber Turnback	K	10.0			K	10.0		
	Tandem Extra	K	5.0			K	5.0		

Type Codes: G = Gamma K = Constant W = Weibull
Pn = Parameter n (See Appendix G)
All numerical values are minutes.

TABLE E-3
LOCKING TIME INPUT DATA; PEDRO MIGUEL LOCKS, REGULAR LOCKAGE

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
1	Approach, Fly/Exchange	G	8.5	1.0	2.0	G	10.2	2.1	2.0
	Approach, Turnback	G	6.4	1.0	2.0	G	7.7	1.0	2.0
	Entry	K	4.0			K	4.0		
	Chambering	G	9.0	1.0	6.0	G	10.0	1.0	5.0
	Exit	K	4.0			K	4.0		
2	Approach, Fly/Exchange	G	8.5	1.0	2.0	G	10.2	2.1	2.0
	Approach, Turnback	G	6.4	1.0	2.0	G	7.7	1.0	2.0
	Entry	K	4.0			K	4.0		
	Chambering	G	9.0	1.0	6.0	G	10.0	1.0	5.0
	Exit	K	5.0			K	5.0		
3	Approach, Fly/Exchange	G	8.5	1.0	2.0	G	10.2	2.1	2.0
	Approach, Turnback	G	6.4	1.0	2.0	G	7.7	1.0	2.0
	Entry	K	6.0			K	6.0		
	Chambering	G	9.0	1.0	6.0	G	10.0	1.0	5.0
	Exit	K	5.0			K	5.0		
4	Approach, Fly/Exchange	G	9.5	1.0	3.0	G	11.2	1.0	4.0
	Approach, Turnback	G	7.1	1.0	3.0	G	8.4	1.0	3.0
	Entry	K	6.0			K	6.0		
	Chambering	G	15.0	1.0	11.0	G	16.0	1.0	11.0
	Exit	K	5.0			K	5.0		

Table E-3 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
5	Approach, Fly/Exchange	G	9.5	1.0	3.0	G	11.2	1.0	4.0
	Approach, Turnback	G	7.1	1.0	3.0	G	8.4	1.0	3.0
	Entry	K	7.0			K	7.0		
	Chambering	G	15.0	1.0	11.0	G	16.0	1.0	11.0
	Exit	K	5.0			K	5.0		
6	Approach, Fly/Exchange	G	12.0	1.5	3.0	G	11.6	1.0	5.0
	Approach, Turnback	G	9.0	1.15	3.0	G	8.7	1.0	4.0
	Entry	K	7.0			K	7.0		
	Chambering	G	16.0	1.0	10.0	G	16.0	1.0	10.0
	Exit	K	5.0			K	5.0		
7	Approach, Fly/Exchange	G	12.0	1.5	3.0	G	11.6	1.0	5.0
	Approach, Turnback	G	9.0	1.15	3.0	G	8.7	1.0	4.0
	Entry	K	7.0			K	7.0		
	Chambering	G	18.0	1.0	12.0	G	18.0	1.0	12.0
	Exit	K	6.0			K	6.0		
8	Approach, Fly/Exchange	G	12.0	1.5	3.0	G	11.6	1.0	5.0
	Approach, Turnback	G	9.0	1.15	3.0	G	8.7	1.0	4.0
	Entry	K	8.0			K	8.0		
	Chambering	G	25.0	1.0	17.0	G	25.0	1.3	17.0
	Exit	K	6.0			K	6.0		

Table E-3 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
9	Approach, Fly/Exchange	G	14.5	1.0	4.0	G	13.0	1.0	5.0
	Approach, Turnback	G	10.9	1.0	3.0	G	9.8	1.0	4.0
	Entry	K	7.0			K	7.0		
	Chambering	G	16.0	1.0	10.0	G	16.0	1.0	10.0
	Exit	K	6.0			K	6.0		
10	Approach, Fly/Exchange	G	14.5	1.0	4.0	G	13.0	1.0	5.0
	Approach, Turnback	G	10.9	1.0	3.0	G	9.8	1.0	4.0
	Entry	K	8.0			K	8.0		
	Chambering	G	24.0	1.0	17.0	G	24.0	1.0	17.0
	Exit	K	7.0			K	7.0		
11	Approach, Fly/Exchange	G	15.0	1.0	5.0	G	13.0	1.15	5.0
	Approach, Turnback	G	10.3	1.0	4.0	G	9.8	1.15	4.0
	Entry	K	8.0			K	8.0		
	Chambering	G	32.0	1.0	22.0	G	32.0	2.0	22.0
	Exit	K	7.0			K	7.0		
12	Approach, Fly/Exchange	G	15.0	1.0	5.0	G	13.0	1.15	5.0
	Approach, Turnback	G	11.3	1.0	4.0	G	9.8	1.15	4.0
	Entry	K	8.0			K	8.0		
	Chambering	G	43.0	2.9	26.0	W	2.5	18.0	22.0
	Exit	K	7.0			K	7.0		

Table E-3 (Continued)

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
13	Approach, Fly/Exchange	G	9.5	1.0	3.0	G	11.2	1.0	4.0
	Approach Turnback	G	7.1	1.0	3.0	G	8.4	1.0	3.0
	Entry	K	6.0			K	6.0		
	Chambering	G	15.0	1.0	11.0	G	16.0	1.0	11.0
	Exit	K	5.0			K	5.0		
14	Approach, Fly/Exchange	W	2.0	7.9	2.0	W	2.0	9.8	2.0
	Approach, Turnback	W	2.0	5.9	2.0	W	2.0	7.4	2.0
	Entry	K	4.0			K	4.0		
	Chambering	G	16.0	1.7	7.0	G	16.0	1.7	7.0
	Exit	K	4.0			K	4.0		
All	Chamber Turnback	K	5.0			K	5.0		
	Tandem Extra	K	5.0			K	5.0		

Type Codes: G = Gamma K = Constant W = Weibull
Pn = Parameter n (See Appendix G)
All numerical values are minutes.

TABLE E-4
LOCKING TIME INPUT DATA; TURNBACK APPROACH, RELAY LOCKAGE

Vessel Class	Northbound				Southbound			
	Type	P1	P2	P3	Type	P1	P2	P3
(a) Gatun Locks								
1	G	7.0	1.0	2.0	G	3.3	1.0	2.0
2	G	7.0	1.0	2.0	G	3.3	1.0	2.0
3	G	7.0	1.0	2.0	G	3.3	1.0	2.0
4	G	8.5	1.0	2.0	G	4.8	1.0	2.0
5	G	8.5	1.0	2.0	G	4.8	1.0	2.0
6	G	10.8	1.0	2.0	G	7.0	1.0	2.0
7	G	10.8	1.0	2.0	G	7.0	1.0	2.0
8	G	10.8	1.0	2.0	G	7.0	1.0	2.0
9	G	12.3	1.2	3.0	G	7.8	1.0	3.0
10	G	12.3	1.2	3.0	G	7.8	1.0	3.0
11	G	12.3	1.1	4.0	G	8.5	1.0	4.0
12	G	12.3	1.1	4.0	G	8.5	1.0	4.0
13	G	8.5	1.0	2.0	G	4.8	1.0	2.0
14	G	7.0	1.0	2.0	G	3.3	1.0	2.0
(b) Miraflores Locks								
1	G	4.0	1.0	2.0	G	4.1	1.0	2.0
2	G	4.0	1.0	2.0	G	4.1	1.0	2.0
3	G	4.0	1.0	2.0	G	4.1	1.0	2.0
4	G	4.1	1.0	2.0	G	4.3	1.0	2.0
5	G	4.1	1.0	2.0	G	4.3	1.0	2.0
6	G	4.4	1.0	2.0	G	5.9	1.0	2.0
7	G	4.4	1.0	2.0	G	5.9	1.0	2.0
8	G	4.4	1.0	2.0	G	5.9	1.0	2.0
9	G	5.0	1.8	3.0	G	7.2	1.0	3.0
10	G	5.0	1.8	3.0	G	7.2	1.0	3.0
11	G	5.7	2.2	3.0	G	7.2	1.0	3.0
12	G	5.7	2.2	3.0	G	7.2	1.0	3.0
13	G	4.1	1.0	2.0	G	4.3	1.0	2.0
14	G	4.0	1.0	2.0	G	4.1	1.0	2.0

Type Code: G = Gamma
Pn = Parameter n (See Appendix G)
All numerical values are minutes.

Note: Chamber Turnback = 0.0 minutes, both locations.

TABLE E-5
VESSEL CHARACTERISTICS INPUT DATA

Vessel Class	Dimensions, feet				Block Coef.	Nominal Capacity DWT	Horse-power
	Length	Beam	Empty Draft	Loaded Draft			
1	343	54	11	22	0.85	12,000	5,600
2	452	66	12	28	0.85	20,000	9,800
3	463	75	13	32	0.85	35,000	12,300
4	544	85	13	34	0.85	40,000	13,000
5	564	86	13	38	0.90	40,000	13,000
6	600	95	13	30	0.85	51,000	14,000
7	600	95	14	36	0.90	52,000	14,000
8	600	95	14	39	0.95	55,000	14,000
9	650	105	13	30	0.90	58,000	16,000
10	700	105	14	36	0.95	60,000	16,000
11	700	105	15	38	0.95	65,000	16,000
12	700	105	15	39	0.95	70,000	16,000
13	575	84	13	25	0.80	13,000	13,000
14	55	15	6	7	0.75	1	200

TABLE E-6
WAM CALIBRATION RESULTS COMPARED WITH PCC LOCKING TIME SCHEDULE

Vessel Class	Source*	Average Locking Times (minutes)				
		Gatun Locks		Pedro Miguel Locks	Miraflores Locks	
		Regular	Relay		Regular	Relay
1	PCC	60	30	30	40	30
	WAM	53	32	27	37	23
2	PCC	60	35	30	40	30
	WAM	53	32	30	37	24
3	PCC	60	35	30	45	35
	WAM	54	32	30	42	28
4	PCC	70	40	40	50	40
	WAM	69	47	37	50	37
5	PCC	70	45	40	50	40
	WAM	68	44	39	50	38
6	PCC	70	40	40	55	40
	WAM	75	52	42	54	39
7	PCC	75	45	45	65	45
	WAM	77	55	43	61	48
8	PCC	85	50	50	70	50
	WAM	94	72	52	70	57
9	PCC	70	45	40	60	45
	WAM	75	51	43	64	49
10	PCC	85	50	50	70	50
	WAM	97	73	53	74	59
11	PCC	105	60	60	80	60
	WAM	121	97	62	84	71
12	PCC	125	75	65	90	60
	WAM	151	128	68	95	83
Tandem	PCC	70	40	40	50	40
	WAM	67	43	39	50	33

*PCC = Marine Bureau Scheduling Table
WAM = Waterway Analysis Model Output, 1990 Calibration

TABLE E-7
WAM CALIBRATION RESULTS COMPARED WITH SDB LOCKING TIMES

Vessel Class	Source*	Northbound Locking Times (minutes)					
		Gatun Locks		Pedro Miguel Locks		Miraflores Locks	
		Average	SD	Average	SD	Average	SD
1	SDB	79	21	34	28	51	13
	WAM	54	15	26	6.8	36	8.3
2	SDB	76	17	33	9.7	48	8.0
	WAM	55	16	28	6.7	36	8.4
3	SDB	76	18	34	9.6	50	11
	WAM	54	17	29	7.1	41	9.0
4	SDB	81	21	36	21	52	9.5
	WAM	72	18	36	7.0	50	8.8
5	SDB	86	17	38	5.5	56	6.9
	WAM	74	16	38	7.1	50	8.9
6	SDB	86	21	41	18	55	10
	WAM	77	18	42	10	54	9.8
7	SDB	91	19	42	13	58	7.8
	WAM	79	20	44	9.2	60	10
8	SDB	95	18	48	22	63	9.1
	WAM	96	18	52	11	69	9.3
9	SDB	93	21	45	18	61	9.1
	WAM	76	19	44	10	65	9.7
10	SDB	101	21	49	16	67	10
	WAM	100	17	54	13	74	10
11	SDB	--	--	--	--	--	--
	WAM	130	22	62	13	86	11
12	SDB	118	23	61	13	85	11
	WAM	149	22	73	14	101	12

*SDB = Ship Data Bank Records, 1990
WAM = Waterway Analysis Model Output, 1990 Calibration

TABLE E-7 (Continued)

Vessel Class	Source*	Southbound Locking Times (minutes)					
		Gatun Locks		Pedro Miguel Locks		Miraflores Locks	
		Average	SD	Average	SD	Average	SD
1	SDB	70	13	36	13	51	14
	WAM	51	13	29	7.4	37	9.7
2	SDB	70	14	36	13	49	9.9
	WAM	51	13	32	7.9	37	9.3
3	SDB	71	14	36	14	50	10
	WAM	51	13	32	7.3	42	9.3
4	SDB	75	15	38	12	53	12
	WAM	66	14	39	7.7	51	10
5	SDB	77	14	44	16	51	9.2
	WAM	67	13	39	7.6	51	11
6	SDB	79	15	41	12	56	15
	WAM	71	17	40	9.6	55	12
7	SDB	86	19	42	10	60	16
	WAM	75	14	43	7.8	61	14
8	SDB	92	16	45	8.7	62	15
	WAM	92	17	51	10	70	13
9	SDB	87	11	42	11	62	15
	WAM	72	17	42	9.5	63	13
10	SDB	93	13	47	9.9	65	14
	WAM	94	19	52	11	73	15
11	SDB	102	17	49	7.4	69	15
	WAM	116	16	62	11	82	13
12	SDB	124	19	56	10	77	14
	WAM	152	20	66	10	93	16

*SDB = Ship Data Bank Records, 1990
WAM = Waterway Analysis Model Output, 1990 Calibration

TABLE E-8
MAPPING OF WEFA SHIP TYPE INTO VESSEL CLASSES

WEFA Type	Laden or Ballast	Vessel DWT Range					
		0 to 9,999	10,000 to 24,999	25,000 to 39,999	40,000 to 64,999	65,000 to 74,999	80,000+
CB	L	1	3	5	10		
	B	1	3	4	9		
F	L	2	3	7	11		
	B	--	--	--	--		
G	L	1	3	8	11		
	B	1	3	6	9		
R	L	2	3	5	10		
	B	2	3	4	9		
RO	L	1	3	5	10		
	B	--	--	--	--		
V	L	2	3	7	--		
	B	2	3	6	9		
P	L	13					
	B	13					
CD	L	2		5	11	12	
	B	2		4	9	9	
CT	L	2		7	10		
	B	2		6	9		
LP	L	1		4	10		
	B	1		4	9		
T	L	1		7	12		12
	B	1		6	9		9

Data are for 65,000 DWT Design Ship Case, Year 2020. Other cases are similar.
Table entries are WAM vessel classes.

TABLE E-9
LOCKING TIME INPUT DATA; PROPOSED ATLANTIC LOCK, RELAY LOCKAGE

Vessel Class	Locking Time Element	Northbound				Southbound			
		Type	P1	P2	P3	Type	P1	P2	P3
15	Approach, Fly/Exchange	G	23.0	1.2	4.0	G	17.0	1.0	4.0
	Approach, Turnback	G	12.3	1.2	3.0	G	7.8	1.0	3.0
	Entry	K	7.0			K	7.0		
	Chambering	W	2.0	22.6	40.0	W	2.0	24.8	40.0
	Exit	K	6.0			K	6.0		
16	Approach, Fly/Exchange	G	12.0	1.1	5.0	G	18.0	1.0	5.0
	Approach, Turnback	G	12.3	1.1	4.0	G	8.5	1.0	4.0
	Entry	K	10.0			K	10.0		
	Chambering	W	2.0	22.6	61.0	W	2.0	27.1	54.0
	Exit	K	7.0			K	7.0		

Type Codes: G = Gamma K = Constant W = Weibull
Pn = Parameter n (See Appendix G)
All numerical values are minutes.

Note: All other times the same as for Miraflores Locks, Relay Lockage.

TABLE E-10
LOCKING TIME INPUT DATA; CHAMBERING TIME,
PROPOSED PACIFIC LOCK, RELAY LOCKAGE

Vessel Class	Northbound				Southbound			
	Type	P1	P2	P3	Type	P1	P2	P3
11	G	46.0	3.0	32.0	G	42.0	2.9	32.0
12	W	2.0	19.2	42.0	W	2.0	20.3	34.0
15	W	2.0	22.6	40.0	W	2.0	24.8	40.0
16	W	2.0	22.6	51.0	W	2.0	27.1	44.0

Type Codes: G = Gamma K = Constant W = Weibull
Pn = Parameter n (See Appendix G)
All numerical values are minutes.

Note: All other times the same as for the proposed Atlantic Lock, Relay Lockage.

APPENDIX F

FUTURE VESSEL TRANSITS

APPENDIX F
FUTURE VESSEL TRANSITS

The capacity of canal alternatives depend, among other things, upon the maximum size of ship and the mix of ships (in terms of size and loading distribution) expected to transit in any year, as well as the physical characteristics of the alternatives. Accordingly, several types of analysis regarding ship traffic were done before the actual capacity analyses were undertaken.

An analysis of historical ship movements was first made and ship movements were organized and categorized by ship type and size. Next, a review was made of the vessel forecast prepared under the Commodity and Traffic Projections Study by the WEFA Group, and the ship type and size categories from those forecasts were related to the Panama Canal Commission (PCC). Finally, for each separate forecast (for different maximum ship sizes and different years), a ship file was generated based on a Poisson distribution, indicating an arrival time for each ship.

SHIP TYPES AND ARRIVALS

The ship types used are based on the beam and draft that are used by the PCC for ship scheduling purposes, as in the locking time data analysis presented in previously in this report, except that the last two classes for 100-ft. beam and over were combined and classes 13 (passenger vessels) and 14 (recreational vessels) were added.

All Ship Data Bank (SDB) vessels were related to vessel types 1 through 14 (see Table F-1) for analysis and for preparation of model inputs. In addition, vessel types 15 through 22, corresponding to ships from 100,000 to 300,000 DWT in size were added for analysis of the lock and sea-level plans.

TABLE F-1
SHIP TYPE AND SIZE

1	Up to 60' beam	12	100'+ beam, >38' draft
2	61-69' beam	13	commercial passenger
3	70-79' beam	14	recreational vessels
4	80-89' beam, <36' draft	15	100,000 DWT ship ballast
5	80-89' beam, >36' draft	16	100,000 DWT ship laden
6	90-99' beam, <30' draft	17	150,000 DWT ship ballast
7	90-99' beam, 30-36' draft	18	150,000 DWT ship laden
8	90-99' beam, >36' draft	19	250,000 DWT ship ballast
9	100'+ beam, <30' draft	20	250,000 DWT ship laden
10	100'+ beam, 30-36' draft	21	300,000 DWT ship ballast
11	100'+ beam, 36-38' draft	22	300,000 DWT ship laden

Ship arrival times were generated randomly as a Poisson process, based on an analysis of the arrival time distribution from the SDB records.

SHIP TRANSIT PROJECTIONS

A summary of the projections prepared by the WEFA Group of ship transits covering ship mixes with five alternative maximum vessel sizes for years 2020 and 2060 appears in Table F-2.

TABLE F-2
PROJECTED TOTAL PANAMA CANAL TRANSITS

Maximum Ship Size (DWT)	No. of Annual Ship Transits		
	Year 1990	Year 2020	Year 2060
65,000	11,520	18,350	24,810
100,000	-	17,620	23,970
150,000	-	18,140	24,670
250,000	-	18,220	24,740
300,000	-	18,210	24,730

Note: Totals are rounded.

Source: Commodity and Traffic Projections Study, The WEFA Group, 1992

The fewest number of transits occurs with ship mixes capped by 100,000 DWT ships. Apparently, compared with the 65,000 DWT mix, the additional cargo subject to capture by virtue of the economies of the larger ship size is not sufficient to balance the greater volume of cargo that can be carried on each larger ship--hence the reduced number of transits. As ship size increases above 100,000 DWT, greater volumes of traffic would be diverted to the canal. The biggest increase in ship transits occurs between the 100,000 DWT and 150,000 DWT ship mixes. The difference in number of transits between the 250,000 DWT and 300,000 DWT categories is not significant.

The distribution of transits between laden and ballasted ships, northbound and southbound, is indicated in Table F-3.

TABLE F-3
DISTRIBUTION OF
TOTAL PANAMA CANAL VESSEL TRANSITS

	Ballast		Laden		Total		
Year : Case	North	South	North	South	North	South	All
1990 : 1	676	1,084	4,806	4,956	5,482	6,040	11,521
2020 : 1	1,043	1,790	7,684	7,833	8,727	9,623	18,350
2020 : 2	995	1,758	7,362	7,509	8,357	9,267	17,624
2020 : 3	1,075	1,757	7,353	7,958	8,428	9,715	18,143
2020 : 4	1,088	1,756	7,351	8,028	8,439	9,784	18,223
2020 : 5	1,087	1,756	7,351	8,021	8,438	9,777	18,215
2060 : 1	1,349	2,304	9,966	11,193	11,315	13,497	24,812
2060 : 2	1,282	2,253	9,689	10,741	10,971	12,994	23,965
2060 : 3	1,385	2,332	9,652	11,298	11,037	13,630	24,667
2060 : 4	1,397	2,332	9,652	11,360	11,049	13,692	24,741
2060 : 5	1,395	2,332	9,652	11,353	11,047	13,685	24,732

1: 65,000 DWT Design Ship
2: 100,000 DWT Design Ship
3: 150,000 DWT Design Ship
4: 250,000 DWT Design Ship
5: 300,000 DWT Design Ship

Source: Commodity and Traffic Projections Study, The WEFA Group, 1992

APPENDIX G

LOCKING TIME PROBABILITY DISTRIBUTION

APPENDIX G

LOCKING TIME PROBABILITY DISTRIBUTIONS

Locking time data are input to the Waterway Analysis Model in the form of probability distributions, specified with a type code and one or more parameters. For this study, all input distributions were either constant, Gamma, or Weibull distributions. The following sections define the parameters used to specify the distributions, and express the mean and variance of each distribution in terms of the parameters.

Type K - Constant

Parameter	$P1 = \mu$	Location and constant value
Density	$f(x) = 1$	$x = \mu$
	$= 0$	otherwise
Mean	μ	
Variance	0	

Type G - Gamma

Parameters	$P1 = \mu$	Mean
	$P2 = \alpha$	Shape parameter
	$P3 = \gamma$	Location parameter

Density

$$f(x) = \frac{(x - \gamma)^{\alpha-1} \exp[-(x - \gamma)/\beta]}{\beta^{\alpha}\, \Gamma(\alpha)} \qquad x > \gamma$$

$$= 0 \qquad \text{otherwise}$$

where β is a scale parameter defined by the variance (see below)

Mean $\mu = \gamma + \alpha\beta$

Variance $\sigma^2 = \alpha\beta^2$

Type W - Weibull

Parameters

$P1 = \alpha$ Shape parameter

$P2 = \beta$ Scale parameter

$P3 = \gamma$ Location parameter

Density

$$f(x) = \alpha \beta^{-\alpha} (x - \gamma)^{\alpha-1} \exp\{-[(x - \gamma)/\beta]^{\alpha}\} \quad x > \gamma$$

$$= 0 \quad \text{otherwise}$$

Mean $\mu = \gamma + \beta u_1$ where $u_k = \Gamma(1 + k/\alpha)$

Variance $\sigma^2 = \beta^2(u_2 - u_1^2)$

APPENDIX H

DELAY CURVES

APPENDIX H

CAPACITY CURVES

Referring to Figure H-1:

t = transit time (average, hours)
q = traffic (ships or tons) per year
T_0 = transit time at $q = 0$
d = average delay $= t - T_0$
Q = annual traffic capacity
D = average delay at $q = Q/2$
$T = T_0 + D$

$$d = \frac{Dq}{Q-q}, \tag{1}$$

or

$$q = \frac{dQ}{D+d} \tag{1a}$$

$$t = T_0 + d \tag{2}$$

To estimate Q and D:

(q_1,d_1), (q_2,d_2) = two data points, $q_1<q_2$, $d_1<d_2$

$$Q = \frac{1-d_1/d_2}{1-(d_1q_2)/(d_2q_1)}q_2 \tag{3}$$

$$D = \frac{d_1(Q-q_1)}{q_1} = \frac{d_2(Q-q_2)}{q_2} \tag{4}$$

<u>Delay Curve with Fixed Component</u>

In systems operating on a fixed cycle, "delay" is not zero at $q = 0$. Thus, referring to the Figure D-1, we now must work with t_i, T, and T_0 rather than with d_i and D. The delay curve equation for this case is:

$$t = T_0 + \frac{q(T-T_0)}{Q-q}, \tag{5}$$

or

$$q = \frac{(t-T_o)\ Q}{(T-T_o) + (t-T_o)} \tag{5a}$$

With three parameters to estimate, we need three data points:

$$(q_1,t_1),\ (q_2,t_2),\ (q_3,t_3),\ \begin{array}{l} q_1<q_2<q_3 \\ t_1<t_2<t_3 \end{array}$$

The equations for estimating the parameters are:

$$K = \left(\frac{t_2-t_1}{t_3-t_1}\right)\left(\frac{q_3-q_1}{q_2-q_1}\right) \tag{6}$$

$$Q = \frac{q_3-Kq_2}{1-K} \tag{7}$$

$$T = \frac{t_2(Q-q_2)(Q-2q_1)-t_1(Q-q_1)(Q-2q_2)}{Q(q_2-q_1)} \tag{8}$$

$$T_0 = \frac{t_1(Q-q_1)-Tq_1}{Q-2q_1} \tag{9}$$

For example, using results from three simulation runs of a proposed sea level canal with tide gates:

$q_1 = 6.023$	$t_1 = 8.15$
$q_2 = 14.558$	$t_2 = 9.28$
$q_3 = 18.068$	$t_3 = 11.44$

where *q* is thousand ships per year and *t* is average delay hours per ship.

The results are:

$K = 0.4847$
$Q = 21.370$ thousand ships/yr
$T = 8.54$ hr.
$T_0 = 7.90$ hr.

so the delay equation is:

$$t = 7.90 + \frac{0.64q}{21.37-q} \tag{10}$$

Note that with this form of the equation, *t* could either be average delay or average transit time (travel plus delay).

It should be noted, for $q_1=0$ and $t_1=0$, that $T_0=0$ and equations (7) and (8) reduce to equations (3) and (4), respectively.

CAPACITY CURVE

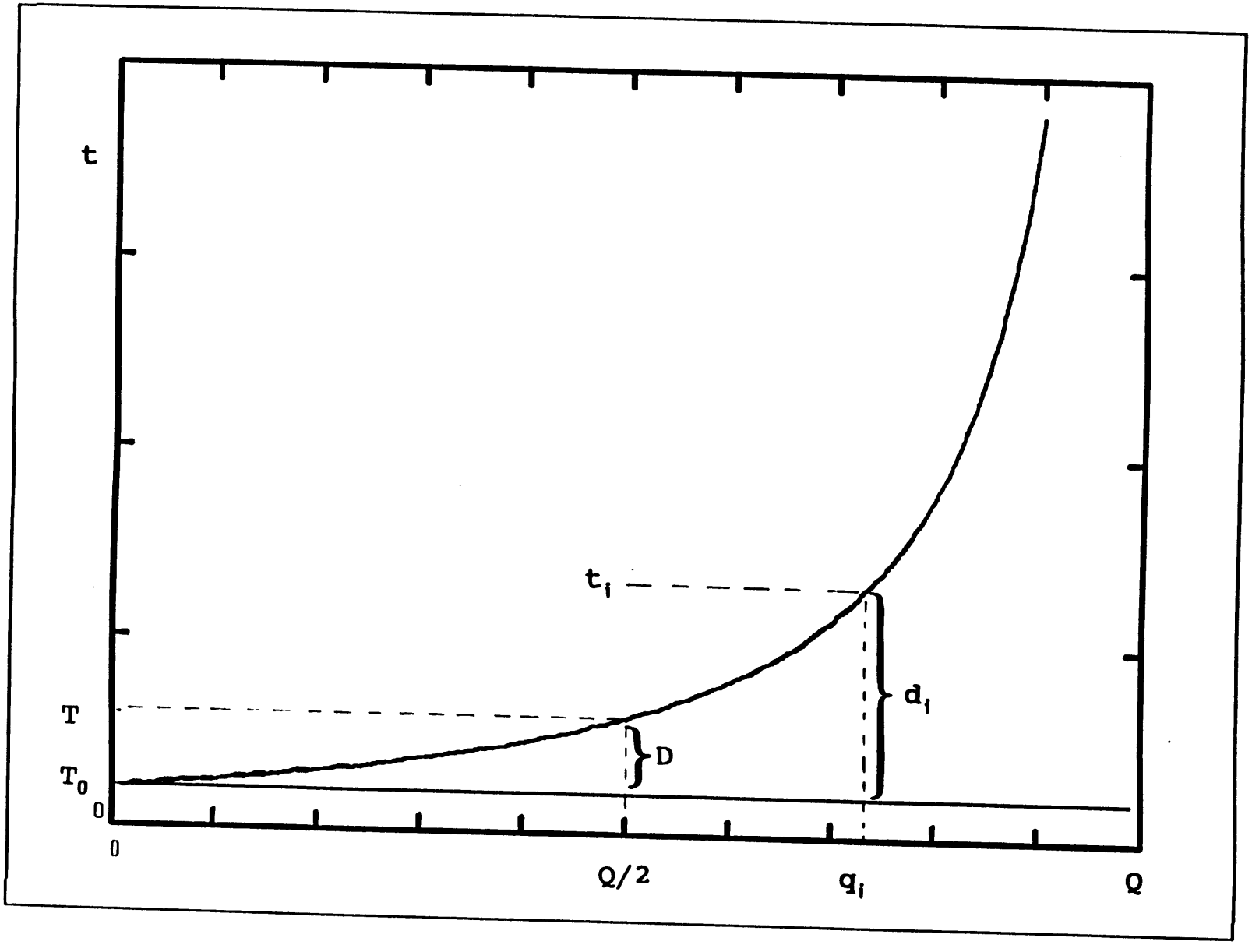

FIGURE H-1

APPENDIX I

PANAMA CANAL SIMULATIONS: SUMMARY OF WAM OUTPUTS

APPENDIX I

PANAMA CANAL SIMULATIONS: SUMMARY OF WAM OUTPUTS

This Appendix provides some summary statistics and descriptions obtained by reviewing the output reports produced by the WAM and the corresponding outputs from the Foxpro postprocessor analyses of the Resource Usage Files. The complete WAM outputs are provided separately on magnetic storage media, and may be viewed and printed with the aid of a personal computer.

A series of tables providing the results of the dynamic routing process are presented, followed by a series of brief narrative descriptions of pertinent WAM results for each study case. These tables and narrative statements are useful for obtaining a greater understanding of the underlying reasons for the capacity estimates provided in the body of the report.

TABLE I-1
PANAMA CANAL SIMULATIONS
Dynamic Routing Results (High Rise Locks)

Case		Route			
		Status Quo	Gatun/ Pacific	Mirafl./ Atlantic	Atlantic/ Pacific
2	Percent Ships	32	19	24	25
	Avg. Transit (Hr.)	17.9	16.6	15.2	15.5
3	Percent Ships	13	20	23	44
	Avg. Transit (Hr.)	29.2	27.6	22.9	22.1
4	Percent Ships	30	20	24	26
	Avg. Transit (Hr.)	23.6	22.6	19.2	19.1
5	Percent Ships	12	19	23	45
	Avg. Transit (Hr.)	25.3	23.6	19.8	18.7
6	Percent Ships	32	19	24	25
	Avg. Transit (Hr.)	19.3	18.1	16.3	16.9
7	Percent Ships	28	20	25	27
	Avg. Transit (Hr.)	25.1	23.5	19.9	20.0

Note: All results are for the WAM run with the highest traffic level. "Atlantic" and "Pacific" refer to the new locks at the North and South ends of the system, respectively.

TABLE I-2
PANAMA CANAL SIMULATIONS
Dynamic Routing Results (Sea Level Canal)

Case			Run 1	Run 2	Run 3
8	Sea Level	Ships/Yr	11,372	26,288	27,406
		Transit (Hr)	8.90	14.13	29.90
	Status Quo	Ships/Yr	8,350	15,196	18,152
		Transit (Hr)	10.03	14.16	24.36
	Total Ships		19,722	41,484	45,558
	% to Sea Level		58	63	60
9	Sea Level	Ships/Yr	2,622	21,424	29,100
		Transit (Hr)	11.40	16.89	23.22
	Status Quo	Ships/Yr	17,064	18,004	18,190
		Transit (Hr)	16.85	34.51	45.71
	Total Ships		19,686	39,428	47,290
	% to Sea Level		13	54	62
10	Sea Level	Ships/Yr	2,564	21,358	29,098
		Transit (Hr)	11.26	15.12	18.24
	Status Quo	Ships/Yr	17,128	18,098	18,252
		Transit (Hr)	16.46	31.29	38.71
	Total Ships		19,692	39,456	47,350
	% to Sea Level		13	54	62

TABLE I-3
PANAMA CANAL SIMULATIONS
Sea Level Canal - Case 9A

		Run 1	Run 2	Run 3
Sea Level	Ships/Yr	2,740	20,100	28,400
	Transit (Hr)	11.42	15.61	19.09
Status Quo	Ships/Yr	16,740	17,800	18,130
	Transit (Hr)	16.89	22.13	39.61
Total Ships		19,480	37,900	46,530
% to Sea Level		14	53	61
% Tandem	Average	6	36	47
	Lane 1	15	48	57
	Lane 2	2	26	39

Note: This Case features one lock 2800 ft. long (Lane 1) and one lock 1400 ft. long (Lane 2), providing the same total lock chamber area as Case 9.

PANAMA CANAL SIMULATIONS

Observations on WAM Outputs for Each Case

Case 1 - Status Quo — Highest Traffic Level = 16,853 Ships

Average delay during transit = 9.2 hours.

Gatun Lock is chief bottleneck, with average delay = 7.7 hours and queues of 7 to 8 ships in each direction. Relay operations 75% of the time.

Approximately 1 tandem lockage per day at Gatun.

Average transit time (excluding delay) very similar in the runs at the two traffic levels; about 9 hours. This similarity condition was observed for all of the cases.

Fog delays minimal - average 0.02 hr. per ship, maximum of 7.4 hr.

Case 1A - Status Quo (PCC Ship Mix) — 15,680 Ships

Basic difference vs. Case 1 is ship mix.

	Case 1	**Case 1A**
% with beam 90 ft.+	34	46
% with beam 100 ft.+	22	34
Avg. Lockage Time (hr.)	2.6	2.8
Avg. Channel Travel (hr.)	6.3	6.4
Total	8.9	9.2

Average delay 15.8 hours.

Gatun lock delay 14.5 hours, queues of 12 to 14 ships each direction. Relay in effect 86% of the time.

Although vessel capacity is lower than Case 1, tonnage capacity is higher.

Case 2 - High Rise, Single Lane Locks, 150K DWT 34,060 Ships

Ship mix : 43% beam 90 ft.+ 24% beam 100 ft.+ 10% 100K DWT+

Average movement time 1 hour less than status quo, due to faster processing at new locks.

Transit times vary from 15.2 hr. to 17.9 hr. across routes.
Routes using existing Gatun locks average 1 to 2 hours longer than routes using new Atlantic lock.

New Atlantic lock has 1.1 hours more delay than new Pacific lock due to higher utilization level as ships seek to avoid delays at Gatun.

New locks attract considerable tandem lockages.

	Atlantic	Pacific
Tandems per day	10	7
Percent tandems	31	23

At lower traffic level, only 8% to 9% of lockages are tandems.

Overall, appears to be a smoothly functioning system.

Case 3 - High Rise, Dual Lane Locks, 150K DWT 53,382 Ships

Ship mix same as Case 2.

Average movement time is slightly less than in Case 2, due to more ships using the new locks, which have average locking time 1.2 hours less than existing locks.

Transit times vary from 22 to 29 hours; routes using Gatun locks average 5 to 7 hours longer than routes using new Atlantic locks.

Variability of time across routes is larger than in Case 2, due primarily to operating at higher utilization level; this is a "near capacity" run, with average lock utilizations of around 94%.

New locks have 35% to 40% tandem lockages.

Case 4 - High Rise, Single Lane Locks, 200K DWT 36,238 ships

Compare with Case 2.

Movement time nearly same as Case 2.

Similar ship mix, but with larger "design ship".

Travel time variability across routes similar to Case 2.

Gatun and new Atlantic locks are the bottlenecks.

Routes using Gatun average 3.5 hours longer than routes using new Atlantic lock.

New locks have 44% (Atlantic) and 33% (Pacific) tandem lockages, vs. 12% at lower traffic level.

Case 5 - High Rise, Dual Lane Locks, 200K DWT 55,574 Ships

Compare with Case 3 (DWT) and Case 4 (No. of Lanes).

Travel times vary from 18.7 to 25.3 hours.
Variability is similar to Case 3, more than Case 4 (since extra set of new locks provides more opportunity for lower transit times).

Continued high level of tandem lockages at new locks: 48% Atlantic, 42% Pacific.

Routes using Gatun have transit times 4 to 6 hours longer than routes using new Atlantic locks.

Case 6 - High Rise, Single Lane Locks, 150K DWT, One-Way Cut 34,528 Ships

Compare with Case 2.

Ships arrive randomly, then are rescheduled to avoid passings in the Culebra Cut when combined beams would exceed 205 ft. (both channel for large ships and the channel into the existing Cut). The rescheduling delay is included in the delay statistics and computation of the delay curve.

Average reschedule delay = 0.44 hours.

Average delay at Cut = 0.4 hours, approximately the same as in the calibration run.

The route selections and average times by route are the same as Case 2.

Average transit delay = 9.9 hours, comparable to Status Quo and to Case 2.

Number of tandem lockages about the same as Case 2.

Therefore, capacity is only slightly degraded, due to the rescheduling delay.

Case 7 - High Rise, Single Lane Locks, 200K DWT, One-Way Cut 36,248 Ships

Compare with Case 4.

Reschedule delay = 0.4 hours.

Average delay at Culebra Cut = 0.5 hours.

Tandem lockage usage same as Case 4.

Travel time and utilization of each route same as Case 4.

Therefore, capacity is only slightly degraded, due to the rescheduling delay.

Case 8 - Sea Level, Tide Gates and Status Quo 45,558 Ships

System behaves quite differently than the High Rise cases.

Route assignments are drastically affected by the cycles of one-way operation.

The 6.25 hour cycle means single lane is closed to arriving ships about 75% of the time.

Missed cycles produce delay of 9 to 12 hours.

Results in about 40% of ships choosing the status quo route.

Transit time difference between routes ranges from 0 to 6 hours.

At highest traffic level the status quo is running close to capacity.

Case 9 - Sea Level, 3 Tidal Locks and Status Quo 47,290 Ships

Cycle time is 12.5 hours, so single lane is closed to arriving ships about 19 hours out of 25.

The delay for missing a cycle is 19 to 25 hours.

Only 13% of the ships go to the sea level canal at low traffic; most of these are the ships too large for the status quo.

Sea level canal use rises to 60% at high traffic, similar to Case 8.

Utilization and delay are very high in the status quo, even at traffic levels that are less than half of the combined system capacity.

Case 10 - Sea Level, 4 Tidal Locks and Status Quo 47,350 Ships

Results very similar to Case 9.

Capacity is higher than Case 9, due to lower delay at the tidal locks.

Case 9A - Sea Level, 2 Tidal Locks (One Long) and Status Quo 46,530 Ships

System has one lock 1400 feet long and one 2800 feet long.

Delay and capacity results very similar to Case 9.

Extensive use of tandem lockages: 47% overall, 57% in long chamber.

System is more vulnerable than case 9, especially if the long chamber goes out of service.

ADDENDUM

This addendum provides output summaries for additional WAM runs made for the following cases:

Water Use Analysis	Cases 2, 4, 8
Capacity Analysis	Cases 8A, 9B

The water use cases consist of simulations of the respective systems for the years 2020 and 2060, using the ship traffic forecasts provided for those years. The added capacity analysis cases involve a single lane approach channel for 15.5 km north of the tide gates (case 8A), and a tidal lock with a single lane (case 9B).

TABLE I-4
PANAMA CANAL SIMULATIONS
Dynamic Routing Results (High Rise Locks)

		Route			
Case		Status Quo	Gatun/ Pacific	Mirafl./ Atlantic	Atlantic/ Pacific
2	Percent Ships	30	23	21	26
	Avg. Transit (Hr.)	10.2	9.2	9.4	9.5
4	Percent Ships	29	23	21	27
	Avg. Transit (Hr.)	10.1	9.1	9.2	9.1

Note: All results are for the WAM run with the highest traffic level. "Atlantic" and "Pacific" refer to the new locks at the North and South ends of the system, respectively.

TABLE I-5
PANAMA CANAL SIMULATIONS
Dynamic Routing Results (Sea Level Canal)

Case			Run 1	Run 2	Run 3
8A	Sea Level Half Cycle	Ships/Yr	10,976	17,756	19,504
		Transit (Hr)	9.14	13.53	39.77
	Status Quo	Ships/Yr	8,730	11,626	17,320
		Transit (Hr)	10.08	11.09	17.63
	Total Ships		19,706	29,382	33,548
	% to Sea Level		56	60	58
8A	Sea Level Full Cycle	Ships/Yr	7,426	17,772	24,584
		Transit (Hr)	12.05	13.61	18.17
	Status Quo	Ships/Yr	12,280	15,800	16,860
		Transit (Hr)	11.28	15.36	17.62
	Total Ships		19,706	33,572	41,444
	% to Sea Level		38	53	59
9B	Sea Level	Ships/Yr	2,506	7,546	10,506
		Transit (Hr)	17.20	20.26	38.66
	Status Quo	Ships/Yr	17,200	17,960	17,960
		Transit (Hr)	17.14	29.18	42.40
	Total Ships		19,706	25,506	28,466
	% to Sea Level		13	30	37
8	Sea Level	Ships/Yr	10,032	14,604	
		Transit (Hr)	8.67	9.09	
	Status Quo	Ships/Yr	8,156	9,650	
		Transit (Hr)	9.71	10.61	
	Total Ships		18,188	24,254	
	% to Sea Level		55	60	

PANAMA CANAL SIMULATIONS

Observations on WAM Outputs for Each Case

Case 2 - High Rise, Single Lane Locks, 150K DWT (Water Use) 24,200 Ships

Results are very similar to the Case 2 run at lower traffic.

Travel time across routes is nearly equalized, ranging from 9.2 to 10.2 hours.

Utilization levels at Gatun and the new locks are 86 to 89 percent, with average delay of 0.9 to 1.1 hours.

Relay operations are used very little (maximum of 15 percent at Gatun, Lane 1).

Case 4 - High Rise, Single Lane Locks, 200K DWT (Water Use) 24,000 ships

Compare with Case 2.

Movement time nearly same as Case 2.

Lockage utilization and delay at the new locks are slightly lower, due to larger chamber size.

Travel time variability across routes similar to Case 2.

Case 8 - Sea Level, Tide Gates and Status Quo (Water Use) 24,254 Ships

Results are very similar to the low traffic run for Case 8.

Average transit time for status quo is about 1.5 hours longer than for sea-level canal.

Case 8A - Sea Level, Tide Gates,
Single Lane Approach and Status Quo 36,824 Ships

This is an approximate simulation of the proposed system.

The results for the half-cycle case are summarized here.

Results are similar to Case 8, in that about 40% of ships choose the status quo. However, traffic levels are much lower for a given transit time, due to the constraining effect of the 15.5 km single lane approach channel.

Spread of travel times is slightly greater than in Case 8 at low and medium traffic levels, and markedly greater at the high traffic level.

The approximate full cycle simulation produces a better traffic and transit time balance.

Case 9B - Sea Level, 1 Tidal Lock and Status Quo 28,466 Ships

Results are very similar to Case 9 at the low traffic level, but differ markedly thereafter.

As in Case 9, only 13% of the ships go to the sea level canal at low traffic; most of these are the ships too large for the status quo.

Sea level canal use rises to only 37% at high traffic, which is the lowest use level of any of the sea-level canal alternatives.

The single lane tidal lock is clearly the controlling element, rather than the delay due to convoy operations. Consequently, transit times for the two routes (sea-level and status quo) are nearly equal at the high traffic level.

PANAMA CANAL SIMULATION
CASE 1 - STATUS QUO - 65,000 DWT - 2020

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	505	3.54	2.10	1.42	7.06	2.31	0.00	2.31	9.37
2	2,140	4.00	2.04	1.58	7.62	4.03	0.00	4.03	11.64
3	4,962	4.62	2.14	1.79	8.55	3.92	0.00	3.92	12.47
4	352	3.88	2.53	1.53	7.93	4.06	0.00	4.06	11.99
5	1,676	4.74	2.56	1.85	9.15	3.92	0.00	3.92	13.07
6	151	4.04	2.69	1.58	8.31	4.04	0.00	4.04	12.35
7	1,623	5.15	2.83	1.99	9.96	3.83	0.00	3.83	13.79
8	47	4.85	3.40	1.88	10.12	4.25	0.00	4.25	14.37
9	376	3.71	2.84	1.47	8.02	3.96	0.00	3.96	11.98
10	242	4.35	3.47	1.71	9.53	4.01	0.00	4.01	13.54
11	1,997	4.93	4.02	1.91	10.86	3.78	0.00	3.78	14.64
12	627	4.85	4.70	1.88	11.43	3.48	0.00	3.48	14.92
13	223	4.13	2.46	1.61	8.20	4.02	0.00	4.02	12.22
	14,921	4.56	2.67	1.78	9.00	3.84	0.00	3.84	12.84

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	577	3.54	2.07	1.42	7.04	4.76	0.00	4.76	11.79
2	2,418	4.00	1.97	1.58	7.55	9.49	0.00	9.49	17.05
3	5,603	4.62	2.06	1.79	8.47	9.44	0.00	9.44	17.91
4	400	3.88	2.44	1.54	7.85	9.62	0.00	9.62	17.47
5	1,895	4.74	2.52	1.85	9.11	9.59	0.00	9.59	18.70
6	172	4.04	2.53	1.57	8.14	9.20	0.00	9.20	17.34
7	1,830	5.15	2.75	1.99	9.89	9.09	0.00	9.09	18.98
8	54	4.84	3.23	1.88	9.95	8.17	0.00	8.17	18.12
9	425	3.70	2.79	1.47	7.96	9.11	0.00	9.11	17.07
10	269	4.35	3.34	1.71	9.40	9.75	0.00	9.75	19.15
11	2,249	4.93	3.91	1.91	10.75	9.15	0.00	9.15	19.90
12	706	4.85	4.52	1.88	11.25	9.11	0.00	9.11	20.37
13	255	4.13	2.37	1.62	8.12	10.11	0.00	10.11	18.23
	16,853	4.56	2.59	1.78	8.92	9.22	0.00	9.22	18.14

PANAMA CANAL SIMULATION
CASE 1A - PCC SHIP MIX - 65,000 DWT - 2010

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	272	3.54	2.08	1.41	7.03	1.16	0.00	1.16	8.19
2	1,144	4.00	2.10	1.57	7.68	1.18	0.00	1.18	8.85
3	2,667	4.62	2.19	1.79	8.60	1.24	0.00	1.24	9.84
4	192	3.88	2.58	1.53	7.99	1.31	0.00	1.31	9.30
5	905	4.75	2.58	1.85	9.18	1.25	0.00	1.25	10.43
6	98	4.04	2.70	1.57	8.30	1.38	0.00	1.38	9.69
7	1,044	5.15	2.91	1.98	10.04	1.19	0.00	1.19	11.22
8	30	4.84	3.33	1.88	10.06	0.98	0.00	0.98	11.04
9	397	3.71	2.87	1.46	8.04	1.28	0.00	1.28	9.32
10	251	4.35	3.47	1.71	9.52	1.17	0.00	1.17	10.69
11	2,087	4.93	4.09	1.91	10.92	1.13	0.00	1.13	12.05
12	654	4.85	4.76	1.88	11.49	1.13	0.00	1.13	12.62
13	144	4.13	2.51	1.61	8.24	1.08	0.00	1.08	9.32
	9,885	4.60	2.94	1.79	9.32	1.20	0.00	1.20	10.52

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	109	3.53	2.05	1.42	7.00	7.70	0.00	7.70	14.70
2	442	4.01	1.93	1.59	7.53	16.11	0.00	16.11	23.64
3	1,073	4.62	2.04	1.80	8.46	15.96	0.00	15.96	24.42
4	66	3.90	2.45	1.55	7.89	14.39	0.00	14.39	22.28
5	359	4.70	2.49	1.83	9.03	15.96	0.00	15.96	24.98
6	40	4.09	2.48	1.59	8.15	15.19	0.00	15.19	23.34
7	411	5.13	2.70	1.98	9.81	17.14	0.00	17.14	26.95
8	11	4.97	3.38	1.94	10.28	15.02	0.00	15.02	25.30
9	160	3.71	2.73	1.48	7.92	16.40	0.00	16.40	24.32
10	96	4.37	3.35	1.72	9.45	15.88	0.00	15.88	25.33
11	820	4.92	3.94	1.91	10.76	15.63	0.00	15.63	26.39
12	276	4.83	4.52	1.87	11.22	15.64	0.00	15.64	26.86
13	57	4.17	2.36	1.62	8.16	15.76	0.00	15.76	23.92
	3,920*	4.59	2.79	1.79	9.17	15.76	0.00	15.76	24.93

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* 92 days of ships.

PANAMA CANAL SIMULATION
CASE 2 - HIGH-RISE - 150,000 DWT - 2060

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	896	3.06	1.79	1.28	6.14	1.34	0.00	1.34	7.48
2	1,936	3.47	1.75	1.45	6.67	1.69	0.00	1.69	8.36
3	9,848	4.07	1.82	1.68	7.57	1.69	0.00	1.69	9.26
4	112	3.55	2.05	1.46	7.06	1.92	0.00	1.92	8.98
5	253	4.01	2.12	1.63	7.76	1.65	0.00	1.65	9.41
6	507	3.65	2.18	1.51	7.35	1.77	0.00	1.77	9.12
7	1,199	4.58	2.25	1.88	8.71	1.68	0.00	1.68	10.39
8	2,790	4.17	2.53	1.71	8.41	1.79	0.00	1.79	10.20
9	409	3.29	2.25	1.39	6.93	1.83	0.00	1.83	8.76
10	373	3.73	2.63	1.54	7.90	1.93	0.00	1.93	9.83
11	123	4.07	2.87	1.70	8.64	2.03	0.00	2.03	10.67
12	2,515	4.30	3.41	1.76	9.47	1.72	0.00	1.72	11.18
13	336	3.66	2.04	1.53	7.24	1.64	0.00	1.64	8.88
15	183	4.03	1.69	1.96	7.68	2.65	0.00	2.65	10.33
16	1,344	4.63	1.72	2.28	8.63	2.30	0.00	2.30	10.93
17	107	4.61	1.75	2.20	8.56	2.45	0.00	2.45	11.02
18	695	4.87	2.06	2.42	9.35	2.18	0.00	2.18	11.52
	23,626	4.07	2.13	1.71	7.91	1.76	0.00	1.76	9.67

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	318	3.04	1.81	1.29	6.15	3.88	0.00	3.88	10.03
2	667	3.53	1.67	1.46	6.66	8.22	0.00	8.22	14.88
3	3,640	4.11	1.75	1.67	7.53	8.62	0.00	8.62	16.15
4	41	3.49	1.91	1.48	6.87	8.31	0.00	8.31	15.19
5	106	4.02	2.02	1.62	7.67	8.75	0.00	8.75	16.42
6	168	3.69	2.05	1.52	7.27	9.16	0.00	9.16	16.42
7	413	4.62	2.17	1.86	8.65	9.04	0.00	9.04	17.69
8	977	4.21	2.45	1.71	8.37	8.97	0.00	8.97	17.33
9	148	3.33	2.15	1.41	6.89	9.30	0.00	9.30	16.18
10	121	3.80	2.52	1.54	7.86	8.55	0.00	8.55	16.41
11	44	4.06	2.73	1.69	8.48	10.27	0.00	10.27	18.74
12	887	4.33	3.26	1.75	9.34	8.96	0.00	8.96	18.30
13	126	3.67	1.93	1.53	7.13	8.40	0.00	8.40	15.53
15	63	4.05	1.58	1.97	7.61	8.71	0.00	8.71	16.31
16	490	4.63	1.57	2.28	8.47	8.85	0.00	8.85	17.32
17	47	4.62	1.65	2.21	8.48	8.04	0.00	8.04	16.52
18	259	4.87	1.82	2.42	9.11	8.95	0.00	8.95	18.06
	8,515	4.10	2.03	1.71	7.84	8.55	0.00	8.55	16.40

PANAMA CANAL SIMULATION
CASE 3 - HIGH-RISE - 150,000 DWT - 2060

Type	Count	Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
		Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	1,151	2.94	1.63	1.35	5.92	0.92	0.00	0.92	6.84
2	2,521	3.35	1.60	1.51	6.47	1.19	0.00	1.19	7.65
3	12,577	3.94	1.65	1.74	7.32	1.17	0.00	1.17	8.50
4	140	3.42	1.85	1.53	6.80	1.43	0.00	1.43	8.23
5	334	3.84	1.80	1.71	7.34	1.34	0.00	1.34	8.68
6	645	3.51	1.87	1.59	6.98	1.25	0.00	1.25	8.23
7	1,525	4.43	1.96	1.94	8.33	1.24	0.00	1.24	9.57
8	3,548	4.03	2.13	1.78	7.93	1.23	0.00	1.23	9.17
9	517	3.19	1.98	1.47	6.64	1.24	0.00	1.24	7.88
10	484	3.58	2.19	1.62	7.40	1.34	0.00	1.34	8.73
11	155	3.94	2.38	1.75	8.07	1.17	0.00	1.17	9.24
12	3,180	4.15	2.77	1.82	8.74	1.28	0.00	1.28	10.02
13	437	3.53	1.81	1.59	6.94	1.13	0.00	1.13	8.06
15	235	4.04	1.68	1.98	7.69	1.39	0.00	1.39	9.08
16	1,722	4.64	1.70	2.29	8.63	1.19	0.00	1.19	9.81
17	135	4.61	1.75	2.22	8.58	1.21	0.00	1.21	9.79
18	876	4.87	2.04	2.43	9.34	1.22	0.00	1.22	10.56
	30,182	3.94	1.88	1.77	7.59	1.20	0.00	1.20	8.79

Type	Count	Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
		Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	1,006	2.95	1.68	1.38	6.01	4.92	0.00	4.92	10.93
2	2,198	3.37	1.54	1.53	6.45	15.67	0.00	15.67	22.12
3	11,167	3.96	1.58	1.75	7.29	17.29	0.00	17.29	24.59
4	114	3.41	1.73	1.56	6.69	18.13	0.00	18.13	24.83
5	302	3.88	1.80	1.70	7.38	18.08	0.00	18.08	25.46
6	598	3.57	1.82	1.59	6.98	18.38	0.00	18.38	25.36
7	1,348	4.47	1.86	1.93	8.26	18.34	0.00	18.34	26.60
8	3,066	4.06	2.03	1.77	7.86	17.75	0.00	17.75	25.61
9	474	3.22	1.91	1.51	6.64	17.89	0.00	17.89	24.52
10	440	3.62	2.07	1.63	7.32	18.23	0.00	18.23	25.55
11	141	4.03	2.31	1.75	8.10	18.99	0.00	18.99	27.09
12	2,785	4.17	2.56	1.82	8.55	18.00	0.00	18.00	26.55
13	396	3.55	1.71	1.61	6.87	17.01	0.00	17.01	23.88
15	197	4.05	1.57	1.99	7.61	15.73	0.00	15.73	23.34
16	1,551	4.65	1.54	2.29	8.48	15.65	0.00	15.65	24.13
17	119	4.61	1.61	2.23	8.46	14.99	0.00	14.99	23.45
18	789	4.87	1.78	2.43	9.08	15.91	0.00	15.91	24.99
	26,691	3.97	1.78	1.78	7.53	16.78	0.00	16.78	24.31

PANAMA CANAL SIMULATION
CASE 4 - HIGH-RISE - 200,000 DWT - 2060

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	944	2.98	1.77	1.26	6.01	1.36	0.00	1.36	7.37
2	2,038	3.42	1.75	1.43	6.59	1.73	0.00	1.73	8.33
3	10,337	4.01	1.82	1.65	7.48	1.80	0.00	1.80	9.28
4	114	3.47	2.09	1.45	7.00	1.86	0.00	1.86	8.87
5	264	3.90	2.05	1.63	7.57	1.82	0.00	1.82	9.39
6	530	3.60	2.13	1.51	7.24	1.83	0.00	1.83	9.07
7	1,259	4.52	2.26	1.85	8.63	1.73	0.00	1.73	10.36
8	2,932	4.10	2.52	1.69	8.31	1.88	0.00	1.88	10.19
9	427	3.23	2.23	1.38	6.84	2.06	0.00	2.06	8.91
10	392	3.65	2.64	1.52	7.81	1.83	0.00	1.83	9.64
11	131	4.03	2.91	1.66	8.61	1.94	0.00	1.94	10.55
12	2,631	4.23	3.38	1.73	9.34	1.79	0.00	1.79	11.13
13	349	3.61	2.03	1.51	7.16	1.78	0.00	1.78	8.94
15	191	3.97	1.53	1.93	7.43	2.26	0.00	2.26	9.70
16	1,413	4.55	1.57	2.24	8.36	2.31	0.00	2.31	10.67
18	94	5.20	1.68	2.52	9.41	2.33	0.00	2.33	11.73
19	94	4.97	1.77	2.37	9.11	2.26	0.00	2.26	11.37
20	522	5.17	2.04	2.58	9.79	2.24	0.00	2.24	12.03
	24,662	4.01	2.11	1.69	7.81	1.83	0.00	1.83	9.64

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	349	2.98	1.82	1.28	6.08	4.45	0.00	4.45	10.53
2	721	3.44	1.65	1.44	6.53	12.96	0.00	12.96	19.49
3	3,901	4.04	1.73	1.65	7.42	13.85	0.00	13.85	21.27
4	43	3.41	1.89	1.48	6.78	13.90	0.00	13.90	20.68
5	102	4.01	2.01	1.63	7.65	13.30	0.00	13.30	20.95
6	185	3.67	2.03	1.51	7.21	14.05	0.00	14.05	21.25
7	450	4.51	2.10	1.85	8.46	13.80	0.00	13.80	22.26
8	1,058	4.13	2.38	1.68	8.19	14.26	0.00	14.26	22.45
9	148	3.28	2.11	1.41	6.79	14.72	0.00	14.72	21.51
10	126	3.68	2.55	1.53	7.76	14.17	0.00	14.17	21.93
11	49	4.05	2.75	1.66	8.46	13.92	0.00	13.92	22.38
12	948	4.26	3.19	1.73	9.17	14.60	0.00	14.60	23.76
13	123	3.63	1.89	1.51	7.03	14.02	0.00	14.02	21.04
15	73	3.99	1.42	1.94	7.35	13.34	0.00	13.34	20.69
16	525	4.53	1.44	2.24	8.21	12.52	0.00	12.52	20.73
18	29	5.22	1.56	2.53	9.31	14.17	0.00	14.17	23.48
19	39	4.98	1.58	2.38	8.93	12.31	0.00	12.31	21.24
20	198	5.18	1.77	2.58	9.53	11.91	0.00	11.91	21.44
	9,067	4.03	1.99	1.69	7.72	13.43	0.00	13.43	21.14

PANAMA CANAL SIMULATION
CASE 5 - HIGH-RISE - 200,000 DWT - 2060

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	1,159	2.87	1.60	1.33	5.79	0.80	0.00	0.80	6.59
2	2,520	3.30	1.59	1.48	6.38	0.99	0.00	0.99	7.37
3	12,656	3.87	1.65	1.72	7.23	1.04	0.00	1.04	8.27
4	145	3.36	1.81	1.49	6.67	1.20	0.00	1.20	7.87
5	332	3.79	1.85	1.67	7.31	1.05	0.00	1.05	8.36
6	646	3.48	1.89	1.57	6.93	1.10	0.00	1.10	8.03
7	1,537	4.35	1.97	1.92	8.24	0.98	0.00	0.98	9.22
8	3,564	3.95	2.14	1.74	7.84	1.06	0.00	1.06	8.90
9	523	3.12	1.93	1.46	6.51	1.12	0.00	1.12	7.63
10	478	3.51	2.22	1.58	7.32	1.19	0.00	1.19	8.51
11	161	3.89	2.48	1.74	8.12	1.06	0.00	1.06	9.17
12	3,192	4.06	2.70	1.80	8.55	1.10	0.00	1.10	9.65
13	435	3.49	1.79	1.59	6.87	0.98	0.00	0.98	7.85
15	235	3.98	1.55	1.95	7.48	1.11	0.00	1.11	8.59
16	1,739	4.55	1.56	2.25	8.36	1.03	0.00	1.03	9.39
18	109	5.21	1.71	2.53	9.45	1.11	0.00	1.11	10.56
19	115	4.97	1.77	2.38	9.11	0.98	0.00	0.98	10.10
20	633	5.18	2.03	2.58	9.79	1.06	0.00	1.06	10.85
	30,179	3.88	1.86	1.75	7.49	1.04	0.00	1.04	8.52

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	1,055	2.88	1.70	1.36	5.94	4.04	0.00	4.04	9.97
2	2,294	3.32	1.54	1.52	6.38	11.51	0.00	11.51	17.89
3	11,730	3.90	1.58	1.73	7.21	13.79	0.00	13.79	21.00
4	126	3.37	1.69	1.55	6.60	14.39	0.00	14.39	20.99
5	307	3.80	1.78	1.69	7.26	13.18	0.00	13.18	20.45
6	618	3.50	1.77	1.59	6.85	14.32	0.00	14.32	21.17
7	1,414	4.39	1.85	1.91	8.15	14.05	0.00	14.05	22.20
8	3,222	3.98	2.01	1.75	7.74	14.33	0.00	14.33	22.07
9	496	3.17	1.88	1.49	6.53	14.18	0.00	14.18	20.72
10	441	3.55	2.18	1.61	7.35	14.86	0.00	14.86	22.21
11	139	3.92	2.22	1.74	7.88	14.00	0.00	14.00	21.88
12	2,906	4.09	2.51	1.80	8.39	14.62	0.00	14.62	23.02
13	409	3.50	1.68	1.61	6.78	13.86	0.00	13.86	20.64
15	209	3.99	1.42	1.96	7.37	12.11	0.00	12.11	19.48
16	1,627	4.56	1.44	2.26	8.26	12.59	0.00	12.59	20.85
18	98	5.19	1.58	2.53	9.31	13.40	0.00	13.40	22.71
19	102	4.98	1.60	2.39	8.97	11.69	0.00	11.69	20.65
20	594	5.18	1.80	2.58	9.56	12.22	0.00	12.22	21.78
	27,787	3.91	1.77	1.76	7.43	13.30	0.00	13.30	20.73

PANAMA CANAL SIMULATION
CASE 6 - ONE-LANE CULEBRA CUT - 150,000 DWT - 2060

Type	Count	Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
		Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	898	3.04	1.78	1.31	6.13	1.41	0.13	1.53	7.67
2	1,935	3.46	1.74	1.47	6.67	1.84	0.19	2.02	8.70
3	9,846	4.07	1.82	1.69	7.58	1.87	0.17	2.04	9.62
4	112	3.54	2.09	1.48	7.11	2.03	0.18	2.21	9.32
5	252	3.99	2.04	1.67	7.69	1.84	0.16	2.00	9.69
6	505	3.63	2.15	1.55	7.33	1.91	0.18	2.09	9.41
7	1,199	4.60	2.29	1.88	8.77	1.78	0.15	1.93	10.70
8	2,791	4.18	2.57	1.72	8.48	1.89	0.16	2.06	10.53
9	410	3.28	2.22	1.41	6.92	1.92	0.28	2.20	9.12
10	372	3.70	2.56	1.57	7.84	1.93	0.18	2.11	9.95
11	122	4.08	3.06	1.72	8.85	2.12	0.19	2.32	11.17
12	2,514	4.31	3.43	1.77	9.51	1.79	0.23	2.02	11.53
13	336	3.64	2.02	1.55	7.22	1.77	0.18	1.95	9.17
15	183	4.03	1.74	1.97	7.74	2.72	0.59	3.32	11.06
16	1,346	4.63	1.72	2.29	8.65	2.43	0.43	2.86	11.51
17	107	4.61	1.76	2.22	8.60	2.57	0.72	3.29	11.89
18	695	4.87	2.03	2.43	9.33	2.33	0.37	2.70	12.03
	23,623	4.07	2.13	1.73	7.93	1.90	0.20	2.10	10.03

Type	Count	Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
		Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	324	3.06	1.83	1.33	6.21	4.18	0.26	4.44	10.65
2	670	3.52	1.67	1.51	6.70	9.26	0.32	9.58	16.28
3	3,689	4.11	1.74	1.71	7.56	9.68	0.35	10.03	17.58
4	41	3.58	2.00	1.52	7.10	10.15	0.36	10.50	17.61
5	106	4.02	2.03	1.67	7.71	9.77	0.41	10.18	17.89
6	166	3.67	2.02	1.58	7.26	9.83	0.44	10.27	17.53
7	417	4.62	2.17	1.88	8.67	10.19	0.28	10.47	19.15
8	992	4.21	2.43	1.73	8.37	9.93	0.29	10.22	18.59
9	152	3.33	2.16	1.44	6.93	10.58	0.56	11.15	18.08
10	126	3.73	2.48	1.58	7.78	9.32	0.38	9.70	17.47
11	44	4.15	2.97	1.68	8.80	11.75	0.32	12.07	20.87
12	901	4.34	3.25	1.78	9.36	9.90	0.37	10.27	19.64
13	131	3.68	1.88	1.58	7.13	9.39	0.21	9.60	16.73
15	64	4.05	1.61	2.00	7.66	9.33	0.86	10.19	17.85
16	495	4.63	1.56	2.30	8.49	9.53	0.68	10.20	18.69
17	47	4.62	1.69	2.24	8.55	8.79	1.07	9.87	18.42
18	267	4.87	1.80	2.44	9.10	9.50	0.53	10.03	19.14
	8,632	4.10	2.02	1.74	7.87	9.52	0.37	9.89	17.76

PANAMA CANAL SIMULATION
CASE 7 - ONE-LANE CULEBRA CUT - 200,000 DWT - 2060

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	904	2.99	1.76	1.29	6.04	1.27	0.15	1.42	7.46
2	1,946	3.41	1.75	1.44	6.60	1.62	0.19	1.81	8.41
3	9,898	4.01	1.81	1.67	7.49	1.68	0.19	1.87	9.37
4	111	3.46	2.02	1.50	6.97	1.59	0.19	1.78	8.76
5	249	3.91	2.06	1.62	7.59	1.76	0.21	1.97	9.56
6	508	3.61	2.13	1.54	7.28	1.65	0.22	1.88	9.16
7	1,208	4.50	2.24	1.87	8.61	1.65	0.18	1.83	10.43
8	2,805	4.10	2.52	1.70	8.32	1.79	0.19	1.97	10.30
9	410	3.25	2.24	1.41	6.89	1.76	0.25	2.01	8.90
10	379	3.67	2.64	1.53	7.83	1.79	0.26	2.05	9.88
11	124	4.06	2.94	1.67	8.67	2.03	0.18	2.21	10.88
12	2,524	4.23	3.40	1.74	9.37	1.70	0.22	1.93	11.30
13	336	3.59	1.96	1.53	7.08	1.47	0.16	1.63	8.71
15	185	3.97	1.56	1.95	7.47	2.50	0.58	3.08	10.55
16	1,352	4.55	1.58	2.25	8.39	2.26	0.45	2.71	11.09
18	91	5.20	1.72	2.54	9.46	2.52	0.49	3.01	12.47
19	90	4.97	1.73	2.38	9.08	2.09	0.65	2.73	11.81
20	502	5.18	2.05	2.58	9.81	2.20	0.34	2.54	12.35
	23,622	4.01	2.11	1.71	7.82	1.73	0.22	1.95	9.77

		Avg. Travel Time (hrs)				Avg. Delay Time (hrs)			Total Transit
Type	Count	Reach	Lock	Cut	Total	Lock	Cut	Total	(Travel+Delay)
1	349	2.98	1.81	1.34	6.13	4.75	0.40	5.16	11.29
2	720	3.42	1.62	1.49	6.53	12.91	0.49	13.40	19.93
3	3,897	4.03	1.72	1.70	7.45	14.44	0.48	14.92	22.37
4	43	3.49	1.95	1.47	6.92	13.69	0.52	14.21	21.13
5	102	3.97	2.03	1.69	7.69	13.93	0.44	14.37	22.06
6	184	3.63	1.95	1.56	7.14	14.77	0.49	15.26	22.40
7	450	4.53	2.13	1.87	8.53	14.02	0.39	14.42	22.95
8	1,060	4.14	2.40	1.72	8.26	14.80	0.44	15.24	23.50
9	147	3.30	2.19	1.47	6.96	15.21	0.62	15.83	22.79
10	126	3.74	2.60	1.57	7.92	14.19	0.50	14.69	22.61
11	48	3.99	2.64	1.73	8.36	13.57	0.36	13.93	22.29
12	950	4.26	3.15	1.76	9.17	15.14	0.49	15.63	24.80
13	123	3.63	1.86	1.55	7.04	13.97	0.32	14.29	21.32
15	73	3.99	1.40	1.98	7.37	13.82	1.17	14.99	22.36
16	523	4.53	1.42	2.27	8.22	12.58	0.74	13.32	21.54
18	29	5.22	1.53	2.58	9.33	15.20	0.55	15.75	25.08
19	39	4.98	1.55	2.44	8.97	12.83	1.20	14.03	23.00
20	199	5.18	1.78	2.59	9.55	11.95	0.60	12.55	22.10
	9,062	4.03	1.98	1.74	7.75	13.86	0.49	14.36	22.11

APPENDIX J

PHASE 1 CAPACITY

DELAY VS. VESSEL TRANSITS

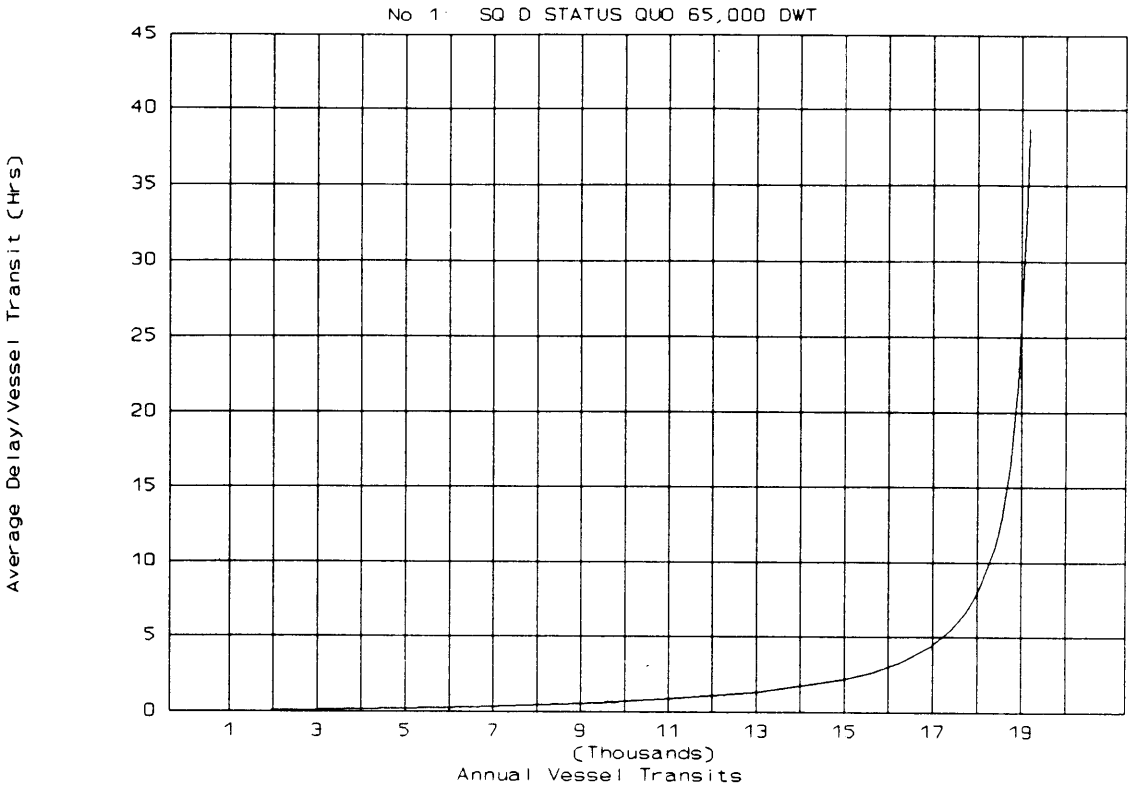
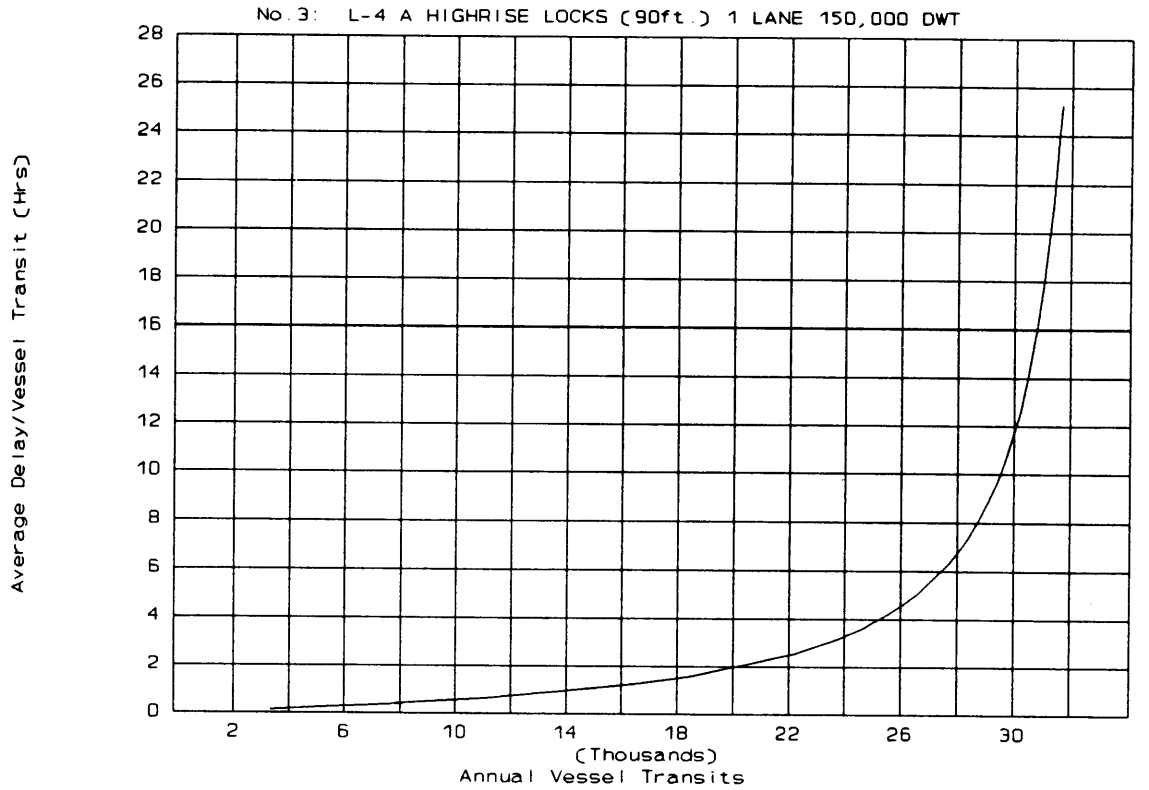


FIGURE J-1

DELAY VS. VESSEL TRANSITS



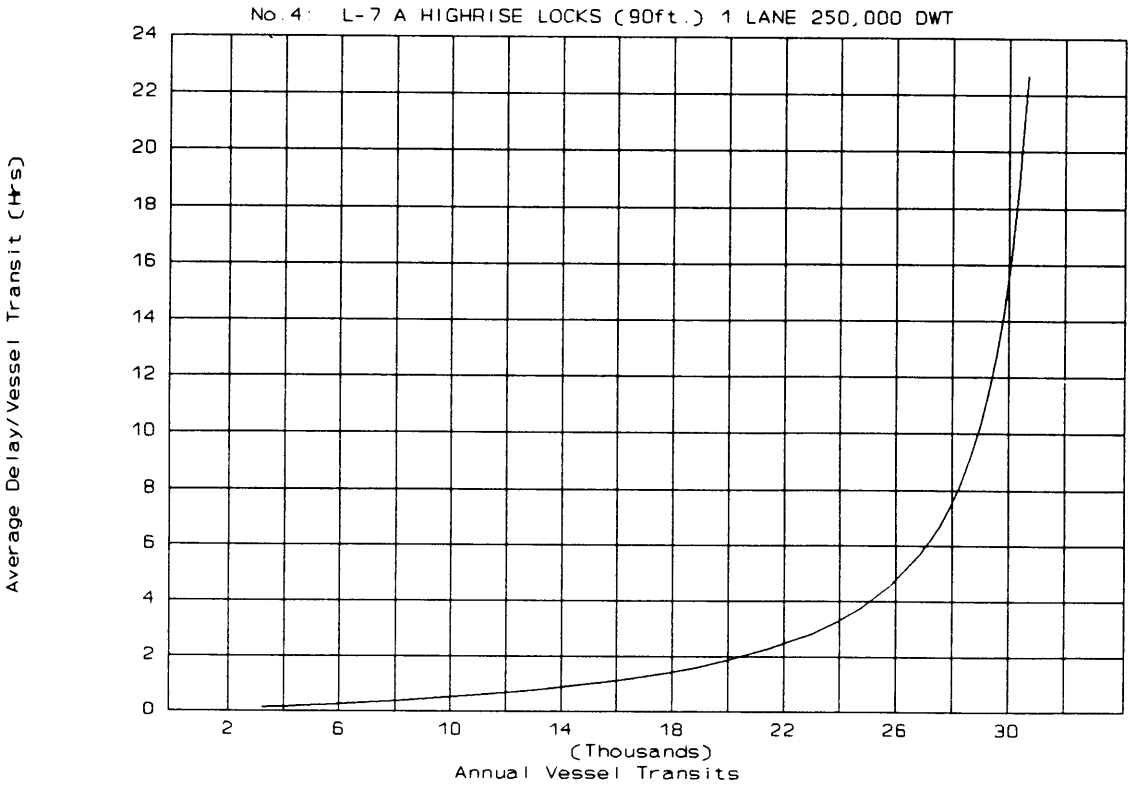


FIGURE J-2

TABLE J-1
TRANSIT DELAYS AND ESTIMATED CAPACITY

TAMS No.	CAS Study Case	Conceptual Alternative	Maximum Ship Size 000s DWT	Average Delay Per Transit (hrs) Fraction of 2020 Transits	Year 2020	Year 2060	Capacity: Annual Transits (No. of Ships) 6 hr. Delay	10 hr. Delay
1	SQ	D Status Quo	65	0.94 (1)	9.68	--	17,600	18,300
2	L-1	A High Rise Locks-90 ft	100	--	1.50	2.53	28,100	30,100
3	L-4	A High Rise Locks-90 ft	150	--	1.51	3.54	27,500	29,500
4	L-7	A High Rise Locks-90 ft	250	--	1.46	3.65	27,100	28,900
5	L-2a	A High Rise Locks-85 ft-Single Lift	100	--	1.50	1.98	29,700	31,900
6	L-3	B Low Rise Locks-55 ft	100	--	0.76	1.03	34,000	35,200
7	L-6	B Low Rise Locks-55 ft	150	--	0.76	1.16	33,400	34,500
8	L-9	B Low Rise Locks-55 ft	250	--	0.76	1.17	33,100	34,200
9	S-1	C Sea Level,1 Lane,Tide Gates,TG(a)	150	8.16 & 8.44 (2)	11.44	--	(5)	15,900
10	S-3	C Sea Level,1 Lane,Tide Gates,TG(a)	250	--	--	--	(5)	15,600
11	S-5	C Sea Level,1 Lane,Tide Gates,TG(a)	300	--	--	--	(5)	15,500
12	S-2	C Sea Level,2 Lanes,Tide Gates,TG(b)	150	--	--	--	33,200	36,800
13	S-4	C Sea Level,2 Lanes,Tide Gates,TG(b)	250	--	--	--	32,400	36,600
14	S-6	C Sea Level,2 Lanes,Tide Gates,TG(b)	300	--	--	--	32,200	36,400
15	S-13	C Sea Level,1 Lane,40 km w/Tide Gates,TG(c)	150	4.18 & 4.32 (2)	8.46	--	16,600	18,400
16	S-14	C Sea Level,1 Lane,40 km w/Tide Gates,TG(c)	250	4.21 & 5.08 (3)	9.38	--	16,200	18,300
17	S-15	C Sea Level,1 Lane,40 km w/Tide Gates,TG(c)	300	--	--	--	16,100	18,200
18	--	- Sea Level,1 Lane,3 Locks,L(a)	250	7.93, 8.63 & 19.55 (4)	--	--	(5)	11,700
19	--	- Sea Level,2 Lanes,6 Locks,L(b)	250	--	0.11	0.23	45,400	46,000
20	--	- Sea Level,2 Lanes,4 Locks,L(c)	250	--	0.27	0.76	29,700	30,100
21	--	- No. 9 + 1	150	--	2.28	3.22	(5)	34,200
22	--	- No. 10 + 1	250	--	2.25	3.20	(5)	33,900
23	--	- No. 15 + 1	150	--	1.88	2.44	34,200	36,700
24	--	- No. 16 + 1	250	--	1.86	2.43	33,800	36,000
25	--	- No. 18 + 1	250	--	2.22	3.16	(5)	30,000

NOTES:

(1) @ 63% of 2020 transits.

(2) @ 33% and 50% of 2020 transits.

(3) @ 33% and 80% of 2020 trasits.

(4) @ 33%, 50% and 80% of 2020 transits.

(5) For these cases, involving 12-1/2 hour cycle convoy operations, 6 hours is not an adequate allowable delay criterion, because 6 hours would be spent on average by ships waiting for convoys to form, allowing no time for in-transit delays.

TABLE J-2
ESTIMATED CAPACITY

CAS Study Case	Conceptual Alternative	Maximum Ship Size 000s DWT	Capacity: Annual Transits (No. of Ships)	
			6 hr.Delay	10 hr.Delay
L-2	A High Rise Locks - 85 ft	100	27,800	30,700
L-5	A High Rise Locks - 85 ft	150	28,100	30,100
L-8	A High Rise Locks - 85 ft	250	27,600	29,500
L-10	A High Rise Locks - 85 ft	100	28,700	30,700
L-11	B Low Rise Lock - 55 ft	100	34,000	35,200
L-12	B Low Rise Lock - 30 ft	100	37,400	38,700
L-13	A High Rise Lock - 85 ft	150	28,100	30,100
L-14	B Low Rise Lock - 55 ft	150	33,400	34,500
L-15	B Low Rise Lock - 30 ft	150	36,700	38,000
L-16	A High Rise Lock - 85 ft	250	27,600	29,500
L-17	B Low Rise Lock - 55 ft	250	33,100	34,200
L-18	B Low Rise Lock - 30 ft	250	36,400	37,600
S-7	C Sea Level Route 14S, 1 lane	150	--	15,900
S-8	C Sea Level Route 14S, 2 lanes	150	33,200	36,800
S-9	C Sea Level Route 14S, 1 lane	250	--	15,600
S-10	C Sea Level Route 14S, 2 lanes	250	32,400	36,600
S-11	C Sea Level Route 14S, 1 lane	300	--	15,500
S-12	C Sea Level Route 14S, 2 lanes	300	32,300	36,400
S-16	C Sea Level Route 14S, 40 km, 1 lane	150	16,600	18,400
S-17	C Sea Level Route 14S, 40 km, 1 lane	250	16,200	18,300
S-18	C Sea Level Route 14S, 40 km, 1 lane	300	16,100	18,200

NOTES: The capacities shown were estimated from similar cases in Table J-1.
CAS Study Cases L-1 through L-9 cover Route 15 + Third Lock
CAS Study Cases L-10 through L-18 cover Route 15 + Gatun + Third Lock

APPENDIX J
TRANSIT DELAY AND CAPACITY

Operational capacity of a transportation artery is not a definitive number, but is related to acceptable delay time. A higher capacity in an artery can be achieved at a cost of greater congestion and longer delays.

In the canal, the level of delay time is related to the rate of ship arrivals, compared with the rate at which ships can transit. With ships arriving in a random fashion, a plot of delay versus the number of transits produces a hyperbolic curve, with delays increasing gradually at low traffic volumes and then accelerating rapidly as traffic continues to increase until, finally, the curve becomes asymptotic at theoretical maximum capacity[1]. The theoretical maximum level of capacity, in practice, is not achievable, nor is it desirable to achieve, because levels of congestion and delays would be excessive. As that level is approached, a slight increase in the number of transits would produce a large increase in delay time.

A more thorough understanding of the relationships of delay, capacity and level of service provided to vessel operators is gained by viewing the entire delay curve. The traffic volume at the design capacity of the transportation system is obtained by selecting the maximum tolerable level of delay, then reading the corresponding number of annual ship transits from the curve. This point may be considered the maximum practicable capacity. The position of this point on the curve shows the effect of small changes in traffic on the expected average delay and, consequently, the stability of operations in the range of the curve. A preferred design capacity is the point of transition from the curved section to the upper, steep, portion of the curve.

Research based on simulation analysis indicates that the delay curve may be plotted from two data points (in our case--at years 2020 and 2060), with the best results achieved if one point is on the flat portion of the curve and the other on the steep portion or the bend of the curve.[2] If both points fall on either the very flat or steep portion of the curve, the results may not produce a reliable curve or specific number, although a judgment can be formed regarding the level of capacity.

In several of the cases modeled, the delay times produced by the model increased relatively slightly between years 2020 and 2060 and the delay in the latter year was less than the criterion, indicating that the case has adequate capacity for year 2060, but also signaling that an actual capacity could not be derived accurately

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1 Davidson, K.B. (1966). *A Flow-Travel Time Relationship for Use in Transportation Planning.* Proceedings, Australian Road Research Board, Melbourne, v. 3, 183-194.

2 Bronzini, M.S. (1984). *Simulation-Based Estimates of Delays at Navigation Locks.* Proceedings, Transportation Research Forum, v.25, n.1, 420-428.

from the delay curve. In those cases (namely 2, 5, 6, 7 and 8)capacity estimates were made by considering separately the simulation results for the existing Gatun Locks and the proposed new Atlantic lock, and using the simulated lock utilization and delay levels to estimate lock capacities, then adding the resultant estimates to obtain the system capacity. These estimates were then adjusted to take into account the relationships among ship mix, weighted average lock processing time, and lock capacity.

The capacities of cases 10 through 14, 17, 19 and 21 through 25 were estimated by comparison with cases with similar characteristics for which capacities had been computed from model runs and the delay curves.

In cases where capacity would be exceeded by the year 2060, it was necessary to model cases with a fraction of the 2020 traffic in order to achieve a second data point. The sea-level cases that are based on a cyclic rhythm of ship convoy transits, in fact, require three data points.

The Panama Canal Commission policy is that ships, on average, should be able to transit within 24 hours of arrival. This criterion appears reasonable and is assumed to continue to obtain in the future. Considering that unimpeded travel time is usually 8 hours or less, and to account for preparation time for canal transit, an average delay of 10 hours was assumed as one basis for capacity. Capacity was also calculated based on 6 hours of delay, except in sea-level cases based on a 12½ hour cycle time, where an average time of 6¼ hours would be spent by ships merely waiting for convoys to form, leaving no time for in-tansit delays.

The capacities of the various conceptual alternatives, calculated as indicated above, are presented in Table J-1. Plots of delay curves appear in Figures J-1 through J-5.

It may be seen, with a ten-hour delay criterion, that the estimated capacities range from a low of 11,700 ship transits for a single lane sea-level canal with three parallel locks at the Pacific, to a high of about 46,000, with a two-lane sea-level canal with six locks. The capacities of the high-rise and low-rise lock plans range from 28,900 transits to 35,200 transits. Capacities with a 6 hour delay criteria are lower.

From the results above, estimates were also made of the capacities of the remaining cases, based on the capacities of similar cases listed in Table J-1, and the results are presented in Table J-2.

The conclusions of the OCCE Study appear together with the summary at the beginning of the report herein.

DELAY VS. VESSEL TRANSITS

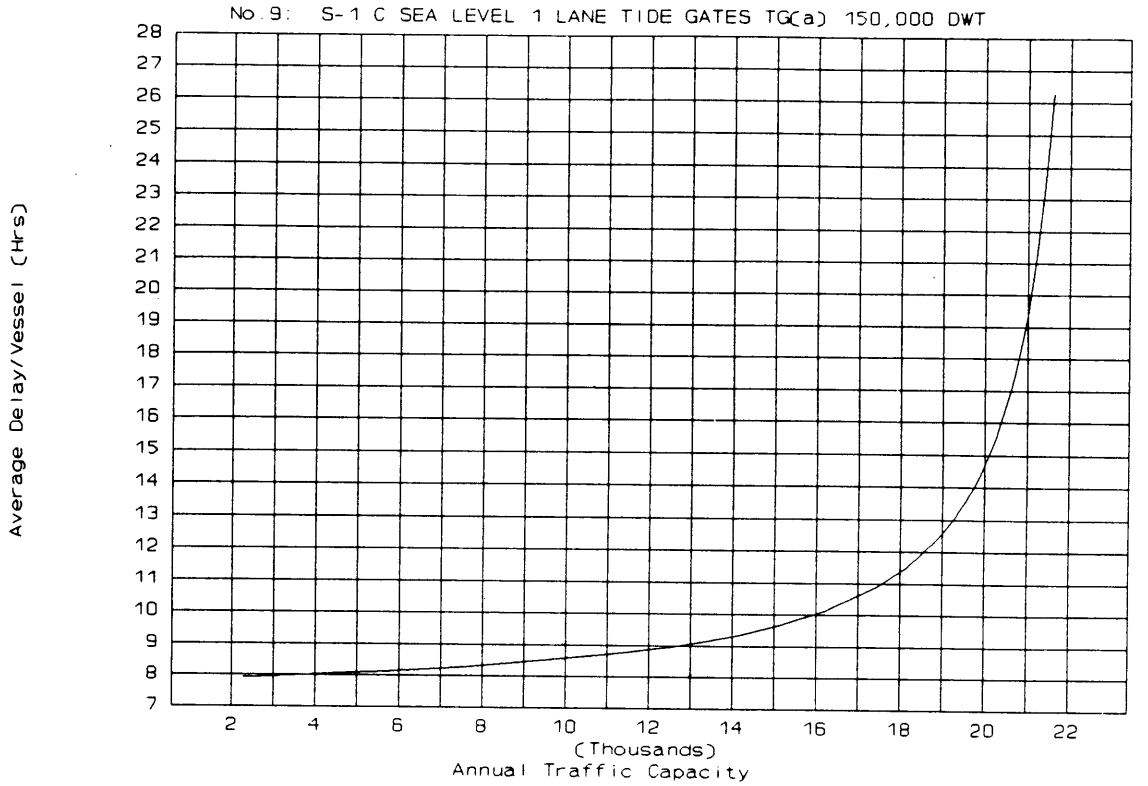
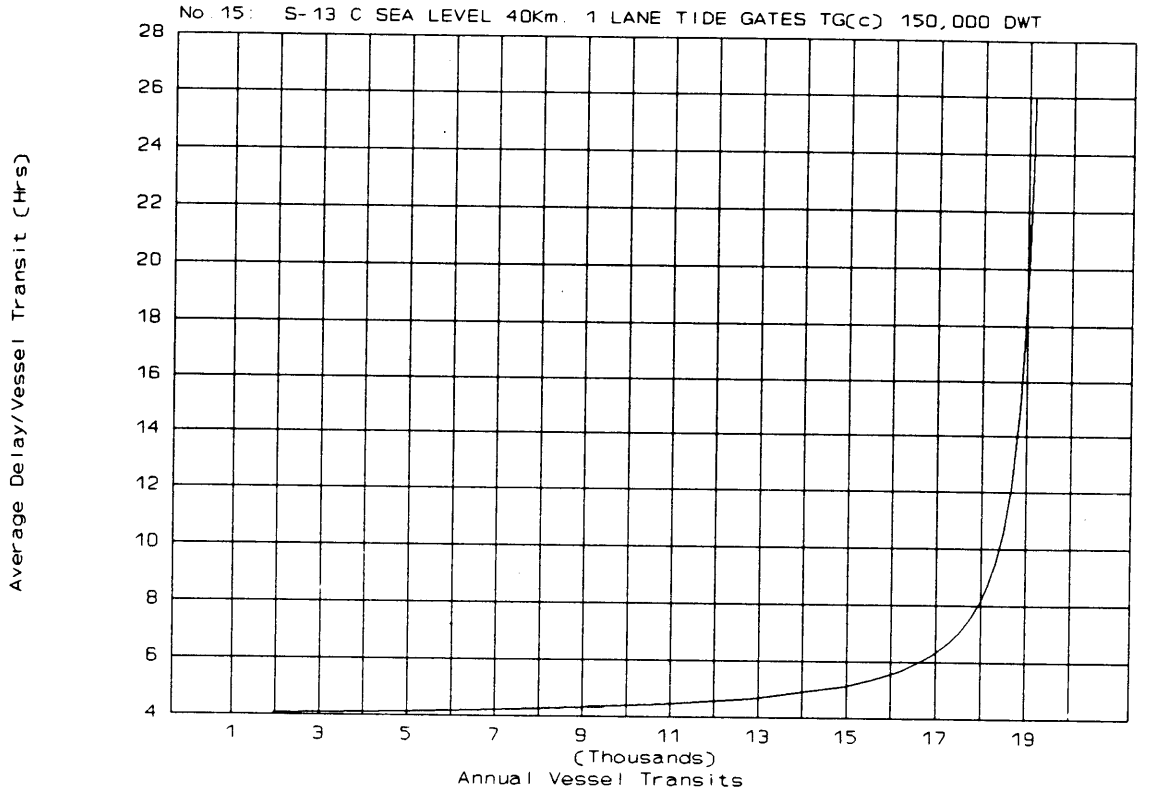


FIGURE J-3

DELAY VS. VESSEL TRANSITS



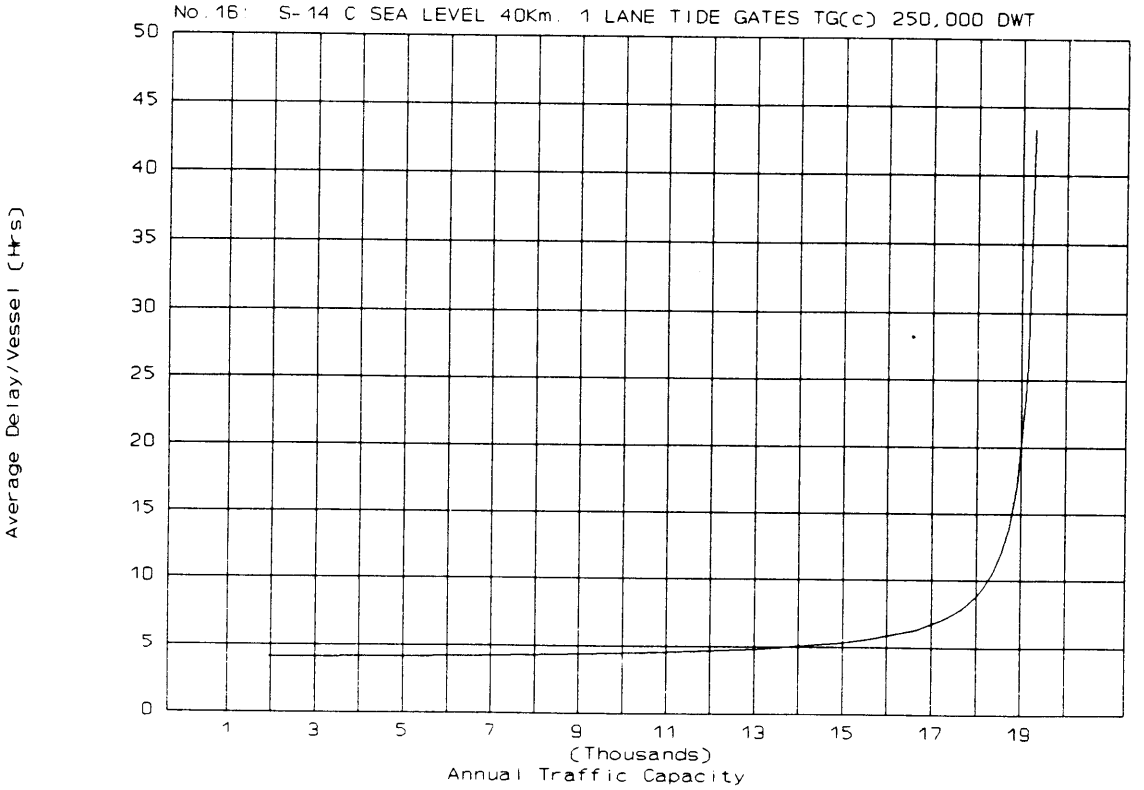
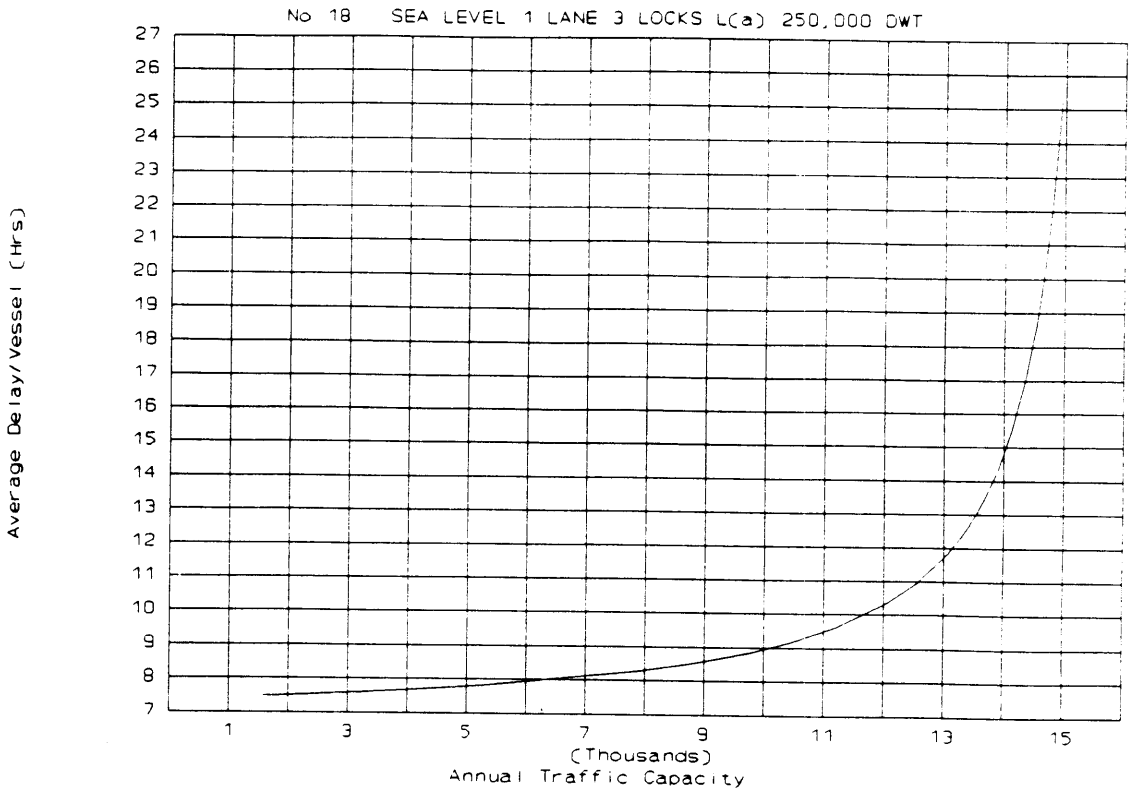


FIGURE J-4

DELAY VS. VESSEL TRANSITS



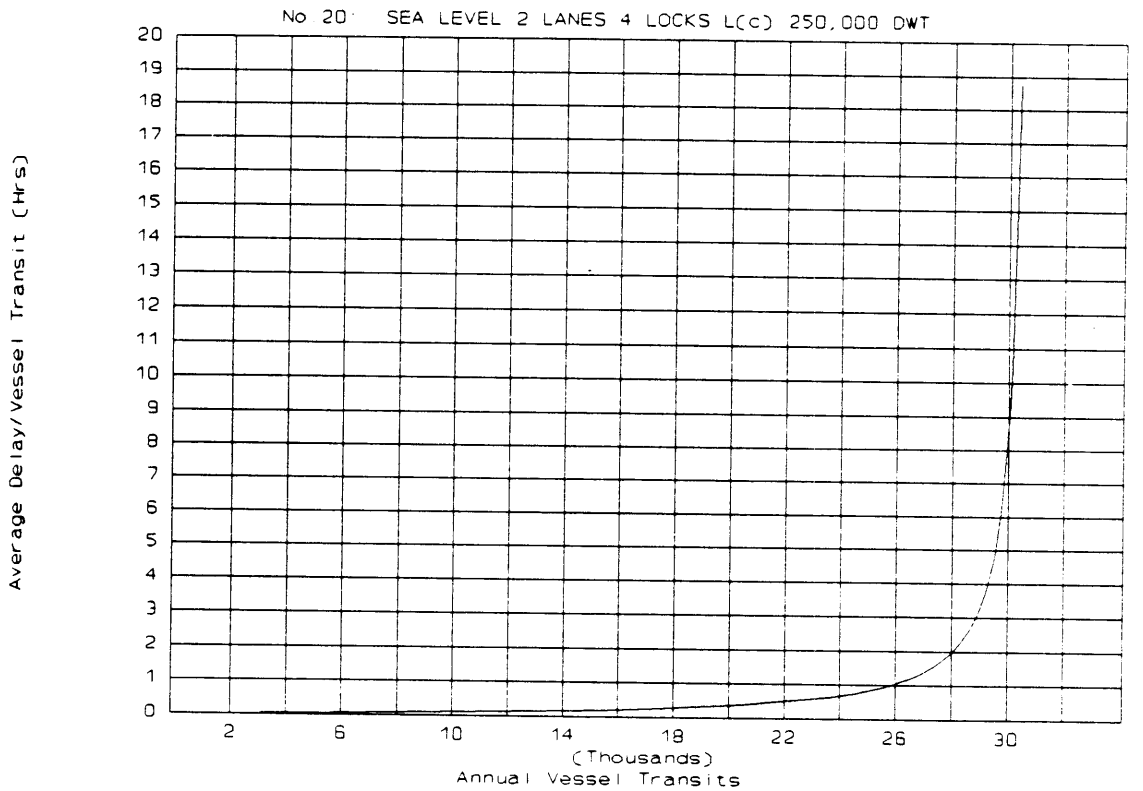


FIGURE J-5

APPENDIX K-1

TYPICAL INPUT DATA FOR PRELATIS

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1 63.3 -80.20 -80.20 63.3/
1 0.025 0.025 0.025/
202 201 -80.20 -80.20 9800. 11 100. 8 4900. 0 0. 0 0. 0 0. 0 0./
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1 0. 340.0 840.0 1180.0/
1 57.8 -78.38 -78.38 57.8/
1 0.025 0.025 0.025/
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1 0. 340.0 840.0 1180./
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PRELAT.DAT 12-3-92 11:28a

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203	202	-47.20	39705.	23122.920	1281.
203	202	-36.20	54087.	37618.590	1334.
203	202	-25.20	69042.	54983.230	1386.
203	202	-14.20	84571.	75104.510	1438.
203	202	-3.20	100673.	97913.760	1490.
203	202	7.80	117348.	123370.100	1542.
203	202	18.80	134597.	151451.300	1594.
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202	201	-69.20	12937.	3735.465	1204.
202	201	-58.20	26492.	11940.920	1260.
202	201	-47.20	40664.	23646.180	1316.
202	201	-36.20	55454.	38499.130	1373.
202	201	-25.20	122471.	44031.160	8200.
202	201	-14.20	212671.	110267.500	8200.
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201	200	-47.20	40664.	23646.180	1316.
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201	200	-25.20	122471.	44031.160	8200.
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201	1	-25.20	172303.	52625.450	14760.
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2	1	-24.96	69451.	55168.160	1400.
2	1	-13.96	85159.	75412.210	1456.
2	1	-2.96	101474.	98387.310	1511.
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3	2	-57.57	25965.	11703.610	1235.
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3	2	-24.57	69435.	55166.440	1400.
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3	2	8.43	118344.	124032.100	1564.
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4	3	-23.67	35441.	26407.330	777.

4	3	-12.67	44292.	36508.210	832.
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5	4	-34.78	26830.	17523.250	720.
5	4	-23.78	35049.	25981.500	775.
5	4	-12.78	43872.	36009.720	830.
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6	5	-34.38	26834.	17526.590	720.
6	5	-23.38	35053.	25985.420	775.
6	5	-12.38	43876.	36014.190	830.
6	5	-1.38	53303.	47640.910	884.
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7	6	-33.98	26834.	17526.600	720.
7	6	-22.98	35053.	25985.430	775.
7	6	-11.98	43876.	36014.190	830.
7	6	-.98	53303.	47640.930	884.
7	6	10.02	63334.	60902.780	939.
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8	7	-55.58	12211.	5303.101	610.
8	7	-44.58	19222.	10628.350	665.
8	7	-33.58	26837.	17529.930	720.
8	7	-22.58	35056.	25989.340	775.
8	7	-11.58	43879.	36018.640	830.
8	7	-.58	53306.	47645.860	884.
8	7	10.42	63338.	60908.150	939.
8	7	21.42	73973.	75848.160	994.
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9	8	-55.19	12208.	5301.051	610.
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9	8	-33.19	26833.	17526.450	720.
9	8	-22.19	35052.	25985.150	775.
9	8	-11.19	43875.	36013.730	830.
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10	9	-21.79	35048.	25980.950	775.
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11	10	-65.40	5802.	1640.694	555.

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11	10	-54.40	12208.	5301.030	610.
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11	10	-32.40	26833.	17526.300	720.
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11	10	-10.40	43874.	36013.270	830.
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12	11	-32.00	26833.	17526.290	720.
12	11	-21.00	35051.	25984.870	775.
12	11	-10.00	43874.	36013.260	830.
12	11	1.00	53301.	47639.500	884.
12	11	12.00	63332.	60900.720	939.
12	11	23.00	73967.	75839.550	994.
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13	12	-53.61	12211.	5303.057	610.
13	12	-42.61	19222.	10628.220	665.
13	12	-31.61	26836.	17529.630	720.
13	12	-20.61	35055.	25988.790	775.
13	12	-9.61	43877.	36017.710	830.
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14	13	-75.21	0.	.000	0.
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14	13	-53.21	12209.	5301.219	610.
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14	13	-31.21	26836.	17527.630	720.
14	13	-20.21	35056.	25987.370	775.
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14	13	12.79	63344.	60909.960	940.
14	13	23.79	73983.	75852.340	995.
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15	14	-52.82	12206.	5299.165	610.
15	14	-41.82	19217.	10623.320	665.
15	14	-30.82	26832.	17524.140	720.
15	14	-19.82	35053.	25983.160	775.
15	14	-8.82	43877.	36012.500	830.
15	14	2.18	53306.	47640.210	885.
15	14	13.18	63340.	60903.540	940.
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16	15	-41.42	19220.	10626.040	665.
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16	15	-19.42	35056.	25987.090	775.
16	15	-8.42	43880.	36016.960	830.
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17	16	-41.02	39845.	23165.410	1290.
17	16	-30.02	54336.	37713.040	1345.
17	16	-19.02	69431.	55159.120	1400.
17	16	-8.02	85130.	75397.200	1455.
17	16	2.98	101434.	98364.200	1510.

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17	16	13.98	118343.	124024.500	1565.
17	16	24.98	135856.	152361.100	1620.
18	17	-73.63	0.	.000	0.
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18	17	-51.63	25965.	11703.690	1235.
18	17	-40.63	39851.	23171.280	1290.
18	17	-29.63	54342.	37720.180	1345.
18	17	-18.63	69437.	55167.440	1400.
18	17	-7.63	85137.	75406.590	1455.
18	17	3.38	101441.	98374.600	1510.
18	17	14.38	118349.	124035.900	1565.
18	17	25.38	135862.	152373.300	1620.
19	18	-73.23	0.	.000	0.
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19	18	-51.23	25959.	11699.230	1235.
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19	18	-29.23	54335.	37712.910	1345.
19	18	-18.23	69430.	55158.890	1400.
19	18	-7.23	85130.	75396.790	1455.
19	18	3.77	101433.	98363.560	1510.
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19	18	25.77	135854.	152359.900	1620.
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20	19	-50.83	25953.	11694.760	1235.
20	19	-39.83	39838.	23159.430	1290.
20	19	-28.83	54329.	37705.630	1345.
20	19	-17.83	69423.	55150.310	1400.
20	19	-6.83	85122.	75386.960	1455.
20	19	4.17	101426.	98352.520	1510.
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300	20	-18.03	335678.	208874.300	9840.
300	20	-7.03	443918.	332309.800	9840.
300	20	3.97	552158.	477350.300	9840.
300	20	14.97	660398.	642345.800	9840.
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301	300	-7.03	85114.	75388.460	1454.
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202	-36.2	536.75
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1	-3.2	4572.52
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3	-2.4	756.19
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4	-24.0	345.40
4	-13.0	432.00
4	-2.0	524.53
4	9.0	622.97
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5	-67.6	56.85
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11	-32.2	262.96
11	-21.2	343.50
11	-10.2	429.97
11	.8	522.35
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12	-64.8	56.87
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12	-31.8	262.98
12	-20.8	343.52
12	-9.8	429.98
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12	12.2	620.67
12	23.2	724.89
13	-75.4	.00
13	-64.4	56.87
13	-53.4	119.66
13	-42.4	188.37
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13	-20.4	343.54
13	-9.4	430.02
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13	12.6	620.73
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14	-64.0	56.85
14	-53.0	119.63
14	-42.0	188.34
14	-31.0	262.98
14	-20.0	343.53
14	-9.0	430.02
14	2.0	522.42
14	13.0	620.75
14	24.0	725.01
15	-74.6	.00
15	-63.6	56.85
15	-52.6	119.63
15	-41.6	188.34
15	-30.6	262.97
15	-19.6	343.53
15	-8.6	430.01
15	2.4	522.42
15	13.4	620.74
15	24.4	725.00
16	-74.2	.00
16	-63.2	90.55
16	-52.2	187.02
16	-41.2	289.42
16	-30.2	397.74
16	-19.2	511.98
16	-8.2	632.15
16	2.8	758.24
16	13.8	890.26
17	-73.8	.00
17	-62.8	124.27
17	-51.8	254.43
17	-40.8	390.51
17	-29.8	532.52
17	-18.8	680.45
17	-7.8	834.31
17	3.2	994.09
17	14.2	1159.79
17	25.2	1331.42
18	-73.4	.00
18	-62.4	124.27
18	-51.4	254.43
18	-40.4	390.51
18	-29.4	532.52
18	-18.4	680.45
18	-7.4	834.31
18	3.6	994.08
18	14.6	1159.79

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18	25.6	1331.41
19	-73.0	.00
19	-62.0	124.21
19	-51.0	254.37
19	-40.0	390.45
19	-29.0	532.45
19	-18.0	680.38
19	-7.0	834.23
19	4.0	994.01
19	15.0	1159.71
20	-73.0	.00
20	-62.0	133.56
20	-51.0	275.99
20	-40.0	869.25
20	-29.0	1554.40
20	-18.0	2242.53
20	-7.0	2933.61
20	4.0	3627.65
20	15.0	4324.66
20	26.0	5024.62
300	-73.0	.00
300	-62.0	135.79
300	-51.0	278.32
300	-40.0	871.67
300	-29.0	1556.92
300	-18.0	2245.13
300	-7.0	2936.29
300	4.0	3630.41
300	15.0	4327.49
300	26.0	5027.53
301	-73.0	.00
301	-62.0	62.12
301	-51.0	127.19
301	-40.0	195.22
301	-29.0	266.21
301	-18.0	340.15
301	-7.0	417.06
301	4.0	496.92
301	15.0	579.73
301	26.0	665.51

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APPENDIX K-2

TYPICAL INPUT DATA FOR LATIS

```
SEALEVEL PANAMA CANAL. ROUTE 10. LATIS RUN 1S. JOB 5419-11. 12/03/92.
TIDES JAN 1-12 92 MAX FLOWS TIDE GATE OPTION, 58 KM LONG, DATA: KS. CHK:.....
    0.025      25.       -1        1.              295          -1.0E06     12114
203                                 -80.2      0.14      20.0        0.
202                                 -80.2      0.14      20.0     9800.       203
201                                 -80.2      0.14      20.0    19600.
200                                 -80.2      0.14      20.0    29400.
  1                                 -80.2      0.14      20.0    45800.
  2                                 -79.8      0.14      20.0    55600.         2
  3                                 -79.4      0.14      20.0    65400.
  4                                 -79.0      0.14      20.0    75200.
  5                                 -78.6      0.14      20.0    85000.
  6                                 -78.2      0.14      20.0    94800.
  7                                 -77.8      0.14      20.0   104600.
  8                                 -77.4      0.14      20.0   114400.
  9                                 -77.0      0.14      20.0   124200.
 10                                 -76.6      0.14      20.0   134000.
 11                                 -76.2      0.14      20.0   143800.
 12                                 -75.8      0.14      20.0   153600.
 13                                 -75.5      0.14      20.0   163400.
 14                                 -75.1      0.14      20.0   173200.
 15                                 -74.7      0.14      20.0   183000.
 16                                 -74.3      0.14      20.0   192800.        15

203          -80.2       .00
203          -69.2     62.04
203          -58.2    126.89
203          -47.2    194.56
203          -36.2    265.03
203          -25.2    338.31
203          -14.2    414.40
203           -3.2    493.30
203            7.8    575.01
203           18.8    659.52
202          -80.2       .00
202          -69.2    125.43
202          -58.2    256.70
202          -47.2    393.81
202          -36.2    536.75
202          -25.2    938.41
202          -14.2   1456.48
202           -3.2   1977.36
202            7.8   2501.05
202           18.8   3027.55
201          -80.2       .00
201          -69.2    232.85
201          -58.2    476.81
201          -47.2    731.86
201          -36.2    998.01
201          -25.2   2613.10
201          -14.2   4828.41
201           -3.2   7043.72
201            7.8   9259.03
201           18.8  11474.34
200          -80.2       .00
200          -69.2     63.39
200          -58.2    129.81
200          -47.2    199.25
200          -36.2    271.73
200          -25.2    600.11
200          -14.2   1042.09
200           -3.2   1484.07
200            7.8   1926.05
200           18.8   2368.03
  1          -80.2       .00
  1          -69.2    167.97
```

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1	-58.2	344.17
1	-47.2	528.38
1	-36.2	720.61
1	-25.2	1752.92
1	-14.2	3161.24
1	-3.2	4572.52
1	7.8	5986.77
1	18.8	7403.99
2	-79.8	.00
2	-68.8	124.27
2	-57.8	254.44
2	-46.8	390.54
2	-35.8	532.58
2	-24.8	680.54
2	-13.8	834.44
2	-2.8	994.26
2	8.2	1160.02
2	19.2	1331.70
3	-79.4	.00
3	-68.4	89.23
3	-57.4	185.68
3	-46.4	287.94
3	-35.4	396.12
3	-24.4	510.22
3	-13.4	630.24
3	-2.4	756.19
3	8.6	888.05
3	19.6	1025.84
4	-79.0	.00
4	-68.0	58.21
4	-57.0	121.13
4	-46.0	189.96
4	-35.0	264.72
4	-24.0	345.40
4	-13.0	432.00
4	-2.0	524.53
4	9.0	622.97
5	-78.6	.00
5	-67.6	56.85
5	-56.6	119.63
5	-45.6	188.33
5	-34.6	262.95
5	-23.6	343.50
5	-12.6	429.96
5	-1.6	522.35
5	9.4	620.66
6	-78.2	.00
6	-67.2	56.86
6	-56.2	119.64
6	-45.2	188.35
6	-34.2	262.97
6	-23.2	343.51
6	-12.2	429.98
6	-1.2	522.37
6	9.8	620.68
6	20.8	724.91
7	-77.8	.00
7	-66.8	56.87
7	-55.8	119.66
7	-44.8	188.36
7	-33.8	262.99
7	-22.8	343.53
7	-11.8	430.00
7	-.8	522.38
7	10.2	620.69
8	-77.4	.00

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8	-66.4	56.87
8	-55.4	119.66
8	-44.4	188.36
8	-33.4	262.98
8	-22.4	343.53
8	-11.4	429.99
8	-.4	522.38
8	10.6	620.69
9	-77.0	.00
9	-66.0	56.85
9	-55.0	119.63
9	-44.0	188.33
9	-33.0	262.95
9	-22.0	343.49
9	-11.0	429.95
9	.0	522.34
9	11.0	620.64
9	22.0	724.87
10	-76.6	.00
10	-65.6	56.85
10	-54.6	119.63
10	-43.6	188.33
10	-32.6	262.95
10	-21.6	343.49
10	-10.6	429.95
10	.4	522.33
10	11.4	620.63
10	22.4	724.86
11	-76.2	.00
11	-65.2	56.86
11	-54.2	119.64
11	-43.2	188.34
11	-32.2	262.96
11	-21.2	343.50
11	-10.2	429.97
11	.8	522.35
11	11.8	620.65
12	-75.8	.00
12	-64.8	56.87
12	-53.8	119.66
12	-42.8	188.36
12	-31.8	262.98
12	-20.8	343.52
12	-9.8	429.98
12	1.2	522.36
12	12.2	620.67
12	23.2	724.89
13	-75.4	.00
13	-64.4	56.87
13	-53.4	119.66
13	-42.4	188.37
13	-31.4	262.99
13	-20.4	343.54
13	-9.4	430.02
13	1.6	522.41
13	12.6	620.73
14	-75.0	.00
14	-64.0	56.85
14	-53.0	119.63
14	-42.0	188.34
14	-31.0	262.98
14	-20.0	343.53
14	-9.0	430.02
14	2.0	522.42
14	13.0	620.75
14	24.0	725.01

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15	-74.6	.00	
15	-63.6	56.85	
15	-52.6	119.63	
15	-41.6	188.34	
15	-30.6	262.97	
15	-19.6	343.53	
15	-8.6	430.01	
15	2.4	522.42	
15	13.4	620.74	
15	24.4	725.00	
16	-74.2	.00	
16	-63.2	90.55	
16	-52.2	187.02	
16	-41.2	289.42	
16	-30.2	397.74	
16	-19.2	511.98	
16	-8.2	632.15	
16	2.8	758.24	
16	13.8	890.26	
203	0.00	-4.5	1
203	0.88	6.5	1
203	7.15	-4.6	1
203	13.52	5.7	1
203	19.45	-3.6	1
203	25.77	6.5	1
203	32.12	-5.0	1
203	38.38	6.0	1
203	44.38	-4.0	1
203	50.55	6.7	1
203	56.88	-5.5	1
203	63.18	6.4	1
203	69.18	-4.5	1
203	75.28	6.9	1
203	81.58	-6.1	1
203	87.85	6.8	1
203	93.85	-5.0	1
203	99.98	7.1	1
203	106.20	-6.5	1
203	112.52	7.2	1
203	118.50	-5.4	1
203	124.63	7.2	1
203	130.82	-6.8	1
203	137.13	7.5	1
203	143.10	-5.7	1
203	149.25	7.3	1
203	155.40	-6.8	1
203	161.72	7.6	1
203	167.70	-5.7	1
203	173.83	7.2	1
203	179.98	-6.6	1
203	186.28	7.6	1
203	192.30	-5.6	1
203	198.38	7.0	1
203	204.55	-6.2	1
203	210.80	7.5	1
203	216.92	-5.3	1
203	222.98	6.6	1
203	229.17	-5.6	1
203	235.38	7.2	1
203	241.57	-4.9	1
203	247.53	6.2	1
203	253.83	-5.0	1
203	259.92	6.9	1
203	266.27	-4.6	1

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203          272.13      5.6          1
203          278.53     -4.4          1
203          284.58      6.5          1
203          291.12     -4.2          1
203          296.90      5.1          1


203 202                          9800.      1.00
202 201                          9800.      1.00
201 200                          9800.      1.00
200   1                         16400.      1.00
  2   1                          9800.      1.00
  3   2                          9800.      1.00
  4   3                          9800.      1.00
  5   4                          9800.      1.00
  6   5                          9800.      1.00
  7   6                          9800.      1.00
  8   7                          9800.      1.00
  9   8                          9800.      1.00
 10   9                          9800.      1.00
 11  10                          9800.      1.00
 12  11                          9800.      1.00
 13  12                          9800.      1.00
 14  13                          9800.      1.00
 15  14                          9800.      1.00
 16  15                          9800.      1.00
111  15                                                          2
        0.     1728.        111  15
     1000.     1728.        111  15
110  11                                                          2
        0.      193.        110  11
     1000.      193.        110  11
109  10                                                          2
        0.       25.        109  10
     1000.       25.        109  10
108   9                                                          2
        0.       22.        108   9
     1000.       22.        108   9
107   8                                                          2
        0.      172.        107   8
     1000.      172.        107   8
106   8                                                          2
        0.       51.        106   8
     1000.       51.        106   8
105   6                                                          2
        0.       12.        105   6
     1000.       12.        105   6
104   5                                                          2
        0.       17.        104   5
     1000.       17.        104   5
103   3                                                          2
        0.      693.        103   3
     1000.      693.        103   3
102   1                                                          2
        0.       68.        102   1
     1000.       68.        102   1
101   1                                                          2
        0.       21.        101   1
     1000.       21.        101   1

203 202       -80.20        0.       .000        0.
203 202       -69.20    12662.  3658.138     1177.
203 202       -58.20    25897. 11685.360     1229.
203 202       -47.20    39705. 23122.920     1281.
203 202       -36.20    54087. 37618.590     1334.
203 202       -25.20    69042. 54983.230     1386.
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203	202	-14.20	84571.	75104.510	1438.
203	202	-3.20	100673.	97913.760	1490.
203	202	7.80	117348.	123370.100	1542.
203	202	18.80	134597.	151451.300	1594.
202	201	-80.20	0.	.000	0.
202	201	-69.20	12937.	3735.465	1204.
202	201	-58.20	26492.	11940.920	1260.
202	201	-47.20	40664.	23646.180	1316.
202	201	-36.20	55454.	38499.130	1373.
202	201	-25.20	122471.	44031.160	8200.
202	201	-14.20	212671.	110267.500	8200.
202	201	-3.20	302871.	198423.800	8200.
202	201	7.80	393071.	305854.200	8200.
202	201	18.80	483271.	430805.600	8200.
201	200	-80.20	0.	.000	0.
201	200	-69.20	12937.	3735.465	1204.
201	200	-58.20	26492.	11940.920	1260.
201	200	-47.20	40664.	23646.180	1316.
201	200	-36.20	55454.	38499.130	1373.
201	200	-25.20	122471.	44031.160	8200.
201	200	-14.20	212671.	110267.500	8200.
201	200	-3.20	302871.	198423.800	8200.
201	200	7.80	393071.	305854.200	8200.
201	200	18.80	483271.	430805.600	8200.
200	1	-80.20	0.	.000	0.
200	1	-69.20	12936.	3735.296	1204.
200	1	-58.20	26486.	11939.800	1260.
200	1	-47.20	40652.	23642.740	1316.
200	1	-36.20	55434.	38491.450	1372.
200	1	-25.20	172303.	52625.450	14760.
200	1	-14.20	334663.	158961.300	14760.
200	1	-3.20	497023.	307003.800	14760.
200	1	7.80	659383.	491266.600	14760.
200	1	18.80	821743.	708304.000	14760.
2	1	-79.96	0.	.000	0.
2	1	-68.96	12678.	3660.337	1180.
2	1	-57.96	25962.	11699.960	1235.
2	1	-46.96	39852.	23167.590	1290.
2	1	-35.96	54349.	37717.880	1345.
2	1	-24.96	69451.	55168.160	1400.
2	1	-13.96	85159.	75412.210	1456.
2	1	-2.96	101474.	98387.310	1511.
2	1	8.04	118394.	124058.100	1566.
2	1	19.04	135921.	152407.900	1621.
3	2	-79.57	0.	.000	0.
3	2	-68.57	12683.	3662.997	1180.
3	2	-57.57	25965.	11703.610	1235.
3	2	-46.57	39851.	23171.040	1290.
3	2	-35.57	54341.	37719.640	1345.
3	2	-24.57	69435.	55166.440	1400.
3	2	-13.57	85134.	75404.930	1455.
3	2	-2.57	101437.	98372.030	1510.
3	2	8.43	118344.	124032.100	1564.
3	2	19.43	135855.	152368.100	1619.
4	3	-78.67	0.	.000	0.
4	3	-67.67	6080.	1768.179	557.
4	3	-56.67	12514.	5508.093	612.
4	3	-45.67	19552.	10905.490	667.
4	3	-34.67	27194.	17877.420	722.
4	3	-23.67	35441.	26407.330	777.
4	3	-12.67	44292.	36508.210	832.
4	3	-1.67	53747.	48208.660	887.
4	3	9.33	63806.	61546.140	942.
4	3	20.33	74470.	76563.510	997.
5	4	-78.78	0.	.000	0.
5	4	-67.78	5799.	1639.445	555.

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5	4	-56.78	12205.	5299.036	610.
5	4	-45.78	19216.	10622.920	665.
5	4	-34.78	26830.	17523.250	720.
5	4	-23.78	35049.	25981.500	775.
5	4	-12.78	43872.	36009.720	830.
5	4	-1.78	53300.	47635.960	884.
5	4	9.22	63331.	60897.380	939.
5	4	20.22	73967.	75836.630	994.
6	5	-78.38	0.	.000	0.
6	5	-67.38	5802.	1640.698	555.
6	5	-56.38	12208.	5301.069	610.
6	5	-45.38	19219.	10625.640	665.
6	5	-34.38	26834.	17526.590	720.
6	5	-23.38	35053.	25985.420	775.
6	5	-12.38	43876.	36014.190	830.
6	5	-1.38	53303.	47640.910	884.
6	5	9.62	63334.	60902.770	939.
6	5	20.62	73970.	75842.390	994.
7	6	-77.98	0.	.000	0.
7	6	-66.98	5802.	1640.700	555.
7	6	-55.98	12208.	5301.072	610.
7	6	-44.98	19219.	10625.640	665.
7	6	-33.98	26834.	17526.600	720.
7	6	-22.98	35053.	25985.430	775.
7	6	-11.98	43876.	36014.190	830.
7	6	-.98	53303.	47640.930	884.
7	6	10.02	63334.	60902.780	939.
7	6	21.02	73970.	75842.410	994.
8	7	-77.58	0.	.000	0.
8	7	-66.58	5805.	1641.949	555.
8	7	-55.58	12211.	5303.101	610.
8	7	-44.58	19222.	10628.350	665.
8	7	-33.58	26837.	17529.930	720.
8	7	-22.58	35056.	25989.340	775.
8	7	-11.58	43879.	36018.640	830.
8	7	-.58	53306.	47645.860	884.
8	7	10.42	63338.	60908.150	939.
8	7	21.42	73973.	75848.160	994.
9	8	-77.19	0.	.000	0.
9	8	-66.19	5802.	1640.697	555.
9	8	-55.19	12208.	5301.051	610.
9	8	-44.19	19219.	10625.580	665.
9	8	-33.19	26833.	17526.450	720.
9	8	-22.19	35052.	25985.150	775.
9	8	-11.19	43875.	36013.730	830.
9	8	-.19	53302.	47640.210	884.
9	8	10.81	63333.	60901.750	939.
9	8	21.81	73968.	75841.000	994.
10	9	-76.79	0.	.000	0.
10	9	-65.79	5799.	1639.441	555.
10	9	-54.79	12205.	5298.996	610.
10	9	-43.79	19215.	10622.790	665.
10	9	-32.79	26830.	17522.950	720.
10	9	-21.79	35048.	25980.950	775.
10	9	-10.79	43871.	36008.800	830.
10	9	.21	53297.	47634.550	884.
10	9	11.21	63328.	60895.340	939.
10	9	22.21	73963.	75833.800	994.
11	10	-76.40	0.	.000	0.
11	10	-65.40	5802.	1640.694	555.
11	10	-54.40	12208.	5301.030	610.
11	10	-43.40	19219.	10625.510	665.
11	10	-32.40	26833.	17526.300	720.
11	10	-21.40	35051.	25984.880	775.
11	10	-10.40	43874.	36013.270	830.
11	10	.60	53301.	47639.500	884.

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11	10	11.60	63332.	60900.720	939.
11	10	22.60	73967.	75839.580	994.
12	11	-76.00	0.	.000	0.
12	11	-65.00	5802.	1640.692	555.
12	11	-54.00	12208.	5301.026	610.
12	11	-43.00	19219.	10625.500	665.
12	11	-32.00	26833.	17526.290	720.
12	11	-21.00	35051.	25984.870	775.
12	11	-10.00	43874.	36013.260	830.
12	11	1.00	53301.	47639.500	884.
12	11	12.00	63332.	60900.720	939.
12	11	23.00	73967.	75839.550	994.
13	12	-75.61	0.	.000	0.
13	12	-64.61	5805.	1641.943	555.
13	12	-53.61	12211.	5303.057	610.
13	12	-42.61	19222.	10628.220	665.
13	12	-31.61	26836.	17529.630	720.
13	12	-20.61	35055.	25988.790	775.
13	12	-9.61	43877.	36017.710	830.
13	12	1.39	53304.	47644.440	884.
13	12	12.39	63335.	60906.090	939.
13	12	23.39	73970.	75845.300	994.
14	13	-75.21	0.	.000	0.
14	13	-64.21	5802.	1640.720	555.
14	13	-53.21	12209.	5301.219	610.
14	13	-42.21	19220.	10626.100	665.
14	13	-31.21	26836.	17527.630	720.
14	13	-20.21	35056.	25987.370	775.
14	13	-9.21	43881.	36017.420	830.
14	13	1.79	53311.	47645.880	885.
14	13	12.79	63344.	60909.960	940.
14	13	23.79	73983.	75852.340	995.
15	14	-74.82	0.	.000	0.
15	14	-63.82	5799.	1639.464	555.
15	14	-52.82	12206.	5299.165	610.
15	14	-41.82	19217.	10623.320	665.
15	14	-30.82	26832.	17524.140	720.
15	14	-19.82	35053.	25983.160	775.
15	14	-8.82	43877.	36012.500	830.
15	14	2.18	53306.	47640.210	885.
15	14	13.18	63340.	60903.540	940.
15	14	24.18	73978.	75845.160	995.
16	15	-74.42	0.	.000	0.
16	15	-63.42	5802.	1640.717	555.
16	15	-52.42	12209.	5301.198	610.
16	15	-41.42	19220.	10626.040	665.
16	15	-30.42	26836.	17527.490	720.
16	15	-19.42	35056.	25987.090	775.
16	15	-8.42	43880.	36016.960	830.
16	15	2.58	53309.	47645.170	885.
16	15	13.58	63343.	60908.930	940.
16	15	24.58	73981.	75850.930	995.

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SEALEVEL PANAMA CANAL. ROUTE 10. LATIS RUN 1S. JOB 5419-11. 12/07/92.
TIDES JAN 1-12 92 MAX FLOWS TIDE GATE OPTION, 58 KM LONG, DATA: KS. CHK:.....
    0.025      25.       -1        1.    .3333      295          -1.0E06     12114
  3                                 -79.4      0.14      20.0     65400.         4
  4                                 -79.0      0.14      20.0     75200.
  5                                 -78.6      0.14      20.0     85000.
  6                                 -78.2      0.14      20.0     94800.
  7                                 -77.8      0.14      20.0    104600.
  8                                 -77.4      0.14      20.0    114400.
  9                                 -77.0      0.14      20.0    124200.
 10                                 -76.6      0.14      20.0    134000.
 11                                 -76.2      0.14      20.0    143800.
 12                                 -75.8      0.14      20.0    153600.
 13                                 -75.5      0.14      20.0    163400.
 14                                 -75.1      0.14      20.0    173200.
 15                                 -74.7      0.14      20.0    183000.
 16                                 -74.3      0.14      20.0    192800.
 17                                 -73.9      0.14      20.0    202600.
 18                                 -73.5      0.14      20.0    212400.
 19                                 -73.1      0.14      20.0    222200.
 20                                 -72.7      0.14      20.0    232000.
224                                 -73.0      0.14      20.0    241800.       225
225                                 -73.0      0.00      20.0    251600.       224

  3          -79.4       .00
  3          -68.4     89.23
  3          -57.4    185.68
  3          -46.4    287.94
  3          -35.4    396.12
  3          -24.4    510.22
  3          -13.4    630.24
  3           -2.4    756.19
  3            8.6    888.05
  3           19.6   1025.84
  4          -79.0       .00
  4          -68.0     58.21
  4          -57.0    121.13
  4          -46.0    189.96
  4          -35.0    264.72
  4          -24.0    345.40
  4          -13.0    432.00
  4           -2.0    524.53
  4            9.0    622.97
  5          -78.6       .00
  5          -67.6     56.85
  5          -56.6    119.63
  5          -45.6    188.33
  5          -34.6    262.95
  5          -23.6    343.50
  5          -12.6    429.96
  5           -1.6    522.35
  5            9.4    620.66
  6          -78.2       .00
  6          -67.2     56.86
  6          -56.2    119.64
  6          -45.2    188.35
  6          -34.2    262.97
  6          -23.2    343.51
  6          -12.2    429.98
  6           -1.2    522.37
  6            9.8    620.68
  6           20.8    724.91
  7          -77.8       .00
  7          -66.8     56.87
  7          -55.8    119.66
  7          -44.8    188.36
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7	-33.8	262.99
7	-22.8	343.53
7	-11.8	430.00
7	-.8	522.38
7	10.2	620.69
8	-77.4	.00
8	-66.4	56.87
8	-55.4	119.66
8	-44.4	188.36
8	-33.4	262.98
8	-22.4	343.53
8	-11.4	429.99
8	-.4	522.38
8	10.6	620.69
9	-77.0	.00
9	-66.0	56.85
9	-55.0	119.63
9	-44.0	188.33
9	-33.0	262.95
9	-22.0	343.49
9	-11.0	429.95
9	.0	522.34
9	11.0	620.64
9	22.0	724.87
10	-76.6	.00
10	-65.6	56.85
10	-54.6	119.63
10	-43.6	188.33
10	-32.6	262.95
10	-21.6	343.49
10	-10.6	429.95
10	.4	522.33
10	11.4	620.63
10	22.4	724.86
11	-76.2	.00
11	-65.2	56.86
11	-54.2	119.64
11	-43.2	188.34
11	-32.2	262.96
11	-21.2	343.50
11	-10.2	429.97
11	.8	522.35
11	11.8	620.65
12	-75.8	.00
12	-64.8	56.87
12	-53.8	119.66
12	-42.8	188.36
12	-31.8	262.98
12	-20.8	343.52
12	-9.8	429.98
12	1.2	522.36
12	12.2	620.67
12	23.2	724.89
13	-75.4	.00
13	-64.4	56.87
13	-53.4	119.66
13	-42.4	188.37
13	-31.4	262.99
13	-20.4	343.54
13	-9.4	430.02
13	1.6	522.41
13	12.6	620.73
14	-75.0	.00
14	-64.0	56.85
14	-53.0	119.63
14	-42.0	188.34

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14	-31.0	262.98
14	-20.0	343.53
14	-9.0	430.02
14	2.0	522.42
14	13.0	620.75
14	24.0	725.01
15	-74.6	.00
15	-63.6	56.85
15	-52.6	119.63
15	-41.6	188.34
15	-30.6	262.97
15	-19.6	343.53
15	-8.6	430.01
15	2.4	522.42
15	13.4	620.74
15	24.4	725.00
16	-74.2	.00
16	-63.2	90.55
16	-52.2	187.02
16	-41.2	289.42
16	-30.2	397.74
16	-19.2	511.98
16	-8.2	632.15
16	2.8	758.24
16	13.8	890.26
17	-73.8	.00
17	-62.8	124.27
17	-51.8	254.43
17	-40.8	390.51
17	-29.8	532.52
17	-18.8	680.45
17	-7.8	834.31
17	3.2	994.09
17	14.2	1159.79
17	25.2	1331.42
18	-73.4	.00
18	-62.4	124.27
18	-51.4	254.43
18	-40.4	390.51
18	-29.4	532.52
18	-18.4	680.45
18	-7.4	834.31
18	3.6	994.08
18	14.6	1159.79
18	25.6	1331.41
19	-73.0	.00
19	-62.0	124.21
19	-51.0	254.37
19	-40.0	390.45
19	-29.0	532.45
19	-18.0	680.38
19	-7.0	834.23
19	4.0	994.01
19	15.0	1159.71
20	-73.0	.00
20	-62.0	133.56
20	-51.0	275.99
20	-40.0	869.25
20	-29.0	1554.40
20	-18.0	2242.53
20	-7.0	2933.61
20	4.0	3627.65
20	15.0	4324.66
20	26.0	5024.62
224	-73.0	.00
224	-62.0	135.79

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224	-51.0	278.32
224	-40.0	871.67
224	-29.0	1556.92
224	-18.0	2245.13
224	-7.0	2936.29
224	4.0	3630.41
224	15.0	4327.49
224	26.0	5027.53
225	-73.0	.00
225	-62.0	62.12
225	-51.0	127.19
225	-40.0	195.22
225	-29.0	266.21
225	-18.0	340.15
225	-7.0	417.06
225	4.0	496.92
225	15.0	579.73
225	26.0	665.51

225	0.00	0.0	1
225	1.75	-0.3	1
225	9.93	1.0	1
225	18.32	-0.5	1
225	23.72	-0.2	1
225	25.73	-0.3	1
225	34.58	1.0	1
225	43.35	-0.5	1
225	59.27	1.0	1
225	68.27	-0.5	1
225	83.92	0.9	1
225	93.03	-0.5	1
225	108.50	0.8	1
225	117.63	-0.5	1
225	133.15	0.7	1
225	142.05	-0.5	1
225	157.80	0.6	1
225	166.42	-0.4	1
225	182.50	0.5	1
225	190.62	-0.4	1
225	198.27	0.2	1
225	201.58	0.1	1
225	207.15	0.4	1
225	214.82	-0.4	1
225	222.12	0.3	1
225	227.32	0.1	1
225	231.95	0.3	1
225	238.95	-0.4	1
225	246.32	0.5	1
225	252.58	0.0	1
225	256.77	0.2	1
225	263.20	-0.4	1
225	270.62	0.6	1
225	277.62	-0.1	1
225	281.63	0.0	1
225	287.40	-0.4	1
225	295.08	0.8	1

4	3	9800.	1.00
5	4	9800.	1.00
6	5	9800.	1.00
7	6	9800.	1.00
8	7	9800.	1.00
9	8	9800.	1.00
10	9	9800.	1.00

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 11  10                          9800.      1.00
 12  11                          9800.      1.00
 13  12                          9800.      1.00
 14  13                          9800.      1.00
 15  14                          9800.      1.00
 16  15                          9800.      1.00
 17  16                          9800.      1.00
 18  17                          9800.      1.00
 19  18                          9800.      1.00
 20  19                          9800.      1.00
115  20                                                          2
       0.      270.        115  20
    1000.      270.        115  20
114  20                                                          2
       0.      204.        114  20
    1000.      204.        114  20
113  18                                                          2
       0.       21.        113  18
    1000.       21.        113  18
112  17                                                          2
       0.       96.        112  17
    1000.       96.        112  17
111  15                                                          2
       0.     1728.        111  15
    1000.     1728.        111  15
110  11                                                          2
       0.      193.        110  11
    1000.      193.        110  11
109  10                                                          2
       0.       25.        109  10
    1000.       25.        109  10
108   9                                                          2
       0.       22.        108   9
    1000.       22.        108   9
107   8                                                          2
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    1000.      172.        107   8
106   8                                                          2
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    1000.       51.        106   8
105   6                                                          2
       0.       12.        105   6
    1000.       12.        105   6
104   5                                                          2
       0.       17.        104   5
    1000.       17.        104   5
103   3                                                          2
       0.      693.        103   3
    1000.      693.        103   3
224  20                          9800.      1.00
225 224                          9800.      1.00

  4   3      -78.67       0.       .000       0.
  4   3      -67.67    6080.   1768.179     557.
  4   3      -56.67   12514.   5508.093     612.
  4   3      -45.67   19552.  10905.490     667.
  4   3      -34.67   27194.  17877.420     722.
  4   3      -23.67   35441.  26407.330     777.
  4   3      -12.67   44292.  36508.210     832.
  4   3       -1.67   53747.  48208.660     887.
  4   3        9.33   63806.  61546.140     942.
  4   3       20.33   74470.  76563.510     997.
  5   4      -78.78       0.       .000       0.
  5   4      -67.78    5799.   1639.445     555.
  5   4      -56.78   12205.   5299.036     610.
  5   4      -45.78   19216.  10622.920     665.
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5	4	-34.78	26830.	17523.250	720.
5	4	-23.78	35049.	25981.500	775.
5	4	-12.78	43872.	36009.720	830.
5	4	-1.78	53300.	47635.960	884.
5	4	9.22	63331.	60897.380	939.
5	4	20.22	73967.	75836.630	994.
6	5	-78.38	0.	.000	0.
6	5	-67.38	5802.	1640.698	555.
6	5	-56.38	12208.	5301.069	610.
6	5	-45.38	19219.	10625.640	665.
6	5	-34.38	26834.	17526.590	720.
6	5	-23.38	35053.	25985.420	775.
6	5	-12.38	43876.	36014.190	830.
6	5	-1.38	53303.	47640.910	884.
6	5	9.62	63334.	60902.770	939.
6	5	20.62	73970.	75842.390	994.
7	6	-77.98	0.	.000	0.
7	6	-66.98	5802.	1640.700	555.
7	6	-55.98	12208.	5301.072	610.
7	6	-44.98	19219.	10625.640	665.
7	6	-33.98	26834.	17526.600	720.
7	6	-22.98	35053.	25985.430	775.
7	6	-11.98	43876.	36014.190	830.
7	6	-.98	53303.	47640.930	884.
7	6	10.02	63334.	60902.780	939.
7	6	21.02	73970.	75842.410	994.
8	7	-77.58	0.	.000	0.
8	7	-66.58	5805.	1641.949	555.
8	7	-55.58	12211.	5303.101	610.
8	7	-44.58	19222.	10628.350	665.
8	7	-33.58	26837.	17529.930	720.
8	7	-22.58	35056.	25989.340	775.
8	7	-11.58	43879.	36018.640	830.
8	7	-.58	53306.	47645.860	884.
8	7	10.42	63338.	60908.150	939.
8	7	21.42	73973.	75848.160	994.
9	8	-77.19	0.	.000	0.
9	8	-66.19	5802.	1640.697	555.
9	8	-55.19	12208.	5301.051	610.
9	8	-44.19	19219.	10625.580	665.
9	8	-33.19	26833.	17526.450	720.
9	8	-22.19	35052.	25985.150	775.
9	8	-11.19	43875.	36013.730	830.
9	8	-.19	53302.	47640.210	884.
9	8	10.81	63333.	60901.750	939.
9	8	21.81	73968.	75841.000	994.
10	9	-76.79	0.	.000	0.
10	9	-65.79	5799.	1639.441	555.
10	9	-54.79	12205.	5298.996	610.
10	9	-43.79	19215.	10622.790	665.
10	9	-32.79	26830.	17522.950	720.
10	9	-21.79	35048.	25980.950	775.
10	9	-10.79	43871.	36008.800	830.
10	9	.21	53297.	47634.550	884.
10	9	11.21	63328.	60895.340	939.
10	9	22.21	73963.	75833.800	994.
11	10	-76.40	0.	.000	0.
11	10	-65.40	5802.	1640.694	555.
11	10	-54.40	12208.	5301.030	610.
11	10	-43.40	19219.	10625.510	665.
11	10	-32.40	26833.	17526.300	720.
11	10	-21.40	35051.	25984.880	775.
11	10	-10.40	43874.	36013.270	830.
11	10	.60	53301.	47639.500	884.
11	10	11.60	63332.	60900.720	939.
11	10	22.60	73967.	75839.580	994.

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12	11	-76.00	0.	.000	0.
12	11	-65.00	5802.	1640.692	555.
12	11	-54.00	12208.	5301.026	610.
12	11	-43.00	19219.	10625.500	665.
12	11	-32.00	26833.	17526.290	720.
12	11	-21.00	35051.	25984.870	775.
12	11	-10.00	43874.	36013.260	830.
12	11	1.00	53301.	47639.500	884.
12	11	12.00	63332.	60900.720	939.
12	11	23.00	73967.	75839.550	994.
13	12	-75.61	0.	.000	0.
13	12	-64.61	5805.	1641.943	555.
13	12	-53.61	12211.	5303.057	610.
13	12	-42.61	19222.	10628.220	665.
13	12	-31.61	26836.	17529.630	720.
13	12	-20.61	35055.	25988.790	775.
13	12	-9.61	43877.	36017.710	830.
13	12	1.39	53304.	47644.440	884.
13	12	12.39	63335.	60906.090	939.
13	12	23.39	73970.	75845.300	994.
14	13	-75.21	0.	.000	0.
14	13	-64.21	5802.	1640.720	555.
14	13	-53.21	12209.	5301.219	610.
14	13	-42.21	19220.	10626.100	665.
14	13	-31.21	26836.	17527.630	720.
14	13	-20.21	35056.	25987.370	775.
14	13	-9.21	43881.	36017.420	830.
14	13	1.79	53311.	47645.880	885.
14	13	12.79	63344.	60909.960	940.
14	13	23.79	73983.	75852.340	995.
15	14	-74.82	0.	.000	0.
15	14	-63.82	5799.	1639.464	555.
15	14	-52.82	12206.	5299.165	610.
15	14	-41.82	19217.	10623.320	665.
15	14	-30.82	26832.	17524.140	720.
15	14	-19.82	35053.	25983.160	775.
15	14	-8.82	43877.	36012.500	830.
15	14	2.18	53306.	47640.210	885.
15	14	13.18	63340.	60903.540	940.
15	14	24.18	73978.	75845.160	995.
16	15	-74.42	0.	.000	0.
16	15	-63.42	5802.	1640.717	555.
16	15	-52.42	12209.	5301.198	610.
16	15	-41.42	19220.	10626.040	665.
16	15	-30.42	26836.	17527.490	720.
16	15	-19.42	35056.	25987.090	775.
16	15	-8.42	43880.	36016.960	830.
16	15	2.58	53309.	47645.170	885.
16	15	13.58	63343.	60908.930	940.
16	15	24.58	73981.	75850.930	995.
17	16	-74.02	0.	.000	0.
17	16	-63.02	12677.	3660.230	1180.
17	16	-52.02	25959.	11699.250	1235.
17	16	-41.02	39845.	23165.410	1290.
17	16	-30.02	54336.	37713.040	1345.
17	16	-19.02	69431.	55159.120	1400.
17	16	-8.02	85130.	75397.200	1455.
17	16	2.98	101434.	98364.200	1510.
17	16	13.98	118343.	124024.500	1565.
17	16	24.98	135856.	152361.100	1620.
18	17	-73.63	0.	.000	0.
18	17	-62.63	12683.	3663.010	1180.
18	17	-51.63	25965.	11703.690	1235.
18	17	-40.63	39851.	23171.280	1290.
18	17	-29.63	54342.	37720.180	1345.
18	17	-18.63	69437.	55167.440	1400.

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18	17	-7.63	85137.	75406.590	1455.
18	17	3.38	101441.	98374.600	1510.
18	17	14.38	118349.	124035.900	1565.
18	17	25.38	135862.	152373.300	1620.
19	18	-73.23	0.	.000	0.
19	18	-62.23	12677.	3660.231	1180.
19	18	-51.23	25959.	11699.230	1235.
19	18	-40.23	39845.	23165.370	1290.
19	18	-29.23	54335.	37712.910	1345.
19	18	-18.23	69430.	55158.890	1400.
19	18	-7.23	85130.	75396.790	1455.
19	18	3.77	101433.	98363.560	1510.
19	18	14.77	118342.	124023.600	1565.
19	18	25.77	135854.	152359.900	1620.
20	19	-72.83	0.	.000	0.
20	19	-61.83	12671.	3657.446	1180.
20	19	-50.83	25953.	11694.760	1235.
20	19	-39.83	39838.	23159.430	1290.
20	19	-28.83	54329.	37705.630	1345.
20	19	-17.83	69423.	55150.310	1400.
20	19	-6.83	85122.	75386.960	1455.
20	19	4.17	101426.	98352.520	1510.
20	19	15.17	118334.	124011.300	1565.
20	19	26.17	135846.	152346.300	1620.
224	20	-73.03	0.	.000	0.
224	20	-62.03	12983.	3745.031	1210.
224	20	-51.03	26630.	11982.100	1271.
224	20	-40.03	119198.	37303.480	9840.
224	20	-29.03	227438.	109335.600	9840.
224	20	-18.03	335678.	208874.300	9840.
224	20	-7.03	443918.	332309.800	9840.
224	20	3.97	552158.	477350.300	9840.
224	20	14.97	660398.	642345.800	9840.
224	20	25.97	768638.	826021.800	9840.
225	224	-73.03	0.	.000	0.
225	224	-62.03	12677.	3660.167	1180.
225	224	-51.03	25957.	11698.830	1235.
225	224	-40.03	39841.	23164.150	1290.
225	224	-29.03	54328.	37710.220	1344.
225	224	-18.03	69419.	55153.880	1399.
225	224	-7.03	85114.	75388.460	1454.
225	224	3.97	101412.	98350.770	1509.
225	224	14.97	118313.	124005.000	1564.
225	224	25.97	135818.	152334.000	1619.

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APPENDIX K-3

DESCRIPTION OF ROUTES PROGRAM

DESCRIPTION OF ROUTES PROGRAM

A quasi two-dimensional numerical model named ROUTES was developed to route suspended sediment and estimate sediment concentrations and bottom deposits, varying with respect to time and space in estuarine harbors and lakes. The model is based on a link-node discretization of the harbor or lake and its neighboring waters. Hydraulic flows through the links and water volumes at the nodes are obtained through use of LATIS. The results from LATIS are stored at desired time intervals and transferred as input to model ROUTES. This model analyzes the fluxes of each sediment class interval into or out of a node and balances these with changes in node concentrations and bottom deposits.

The model does not explicitly account for diffusion-dispersion which is considered much less effective than model advection as a transport mechanism. Dispersion is simulated by establishing a weighed average of adjacent node concentrations to compute the concentration in a link and by changing the integration time interval. This variable is an effective adjustment parameter. Bed scour is accounted by use of sediment transport equation.

MODEL DESCRIPTION

A given model application is started with the assumption of zero initial velocity and elevation. In the case of simulation of a harbor or an estuary, mean tidal cycles (where applicable) at the boundaries are repeated to compute time histories of flows and velocities in the links and elevations at the nodes. The elevations at all nodes at the end and at the beginning of each tidal cycle are compared and the model is assumed to be in steady state when none of the nodes exhibits a difference larger than 3 cm. Normally, two tidal cycles are required to achieve this condition. The locations of the boundary tides are selected at sufficient distances from the area of interest to avoid significant boundary error propagation. Mean tidal ranges and periods at the boundaries are obtained from the National Oceanic and Atmospheric Administration (NOAA) Tide Tables, or other authoritative sources in the country of application. These values are used to compute mean sinusoidal tidal cycles at the boundaries.

In the case of lakes or other non-tidal bodies, this option to seek steady state is not used. Inflow hydrographs of sediment and/or pollutants are usually distributed along the boundaries of a lake or other non-tidal body, at locations of tributary stream inflow.

Model calibration for the tidal case is obtained by adjusting the Manning's friction coefficient in program LATIS until computed tidal ranges are certain tide stations in the estuary are within 3 cm of the mean ranges obtained from the NOAA Tide Tables.

Calibration for the non-tidal case is also achieved through adjustments of Manning's coefficients in LATIS so as to represent a series of known water surface elevations or discharges at several points along the model network.

After calibration, output from LATIS is stored in a file and subsequently used as input for ROUTES to analyze suspended sediment transport, deposition, bed scour and conservative pollutant transport.

SEDIMENT ROUTING

ROUTES analyzes the transport of suspended sediments driven by tidal currents or river inflows and simulates the sediment deposition and bed scour in the estuary or lake. The model uses the same link-node discretization of the estuary or lake as is used by model LATIS and the flow conditions in these nodes and links result from a LATIS precursor run.

This sediment routing model assumes a uniform concentration for the column of water, which is acceptable for fine sediments. Also, it is assumed that suspended sediments travel at the velocity of water. The model does not explicitly account for diffusion and dispersion which are assumed to be much smaller than the advection represented by the fluxes between adjacent nodes as has been reiteratedly demonstrated in other similar studies. To simulate the effects of dispersion, the flux concentrations may be obtained as a weighted average of concentrations at adjacent nodes, in general with a higher weight on the node supplying the flow. An explicit finite-difference solution is obtained for the mass conservation of each fraction diameter of sediments in suspension in volume of a node during a computation time interval. The computation balances the fluxes of sediments entering or leaving the node with the increment or decrement of sediment masses in suspension in the node and the bottom deposits during the same time interval. These masses are converted to volumes using a common deposit dry density.

The following finite-difference expression of the sediment mass balance is written, assuming a deposit dry density of 1.0. A correction may be introduced in the final deposit depth if the deposit density is different.

$$v_i^{n+1} c_i^{n+1} - V_i^n c_i^n - \sum_{j=1}^{m} c_{ij}^n Q_{ij}^n \Delta t + V_i^n c_i^n \frac{w_d \Delta t}{y_i^n} = 0 \qquad (1)$$

in which,

V_i	=	water volume in node i;
c_i	=	concentration in node i (dry weight of suspended material per unit volume);
c_{ij}	=	concentration in flux between nodes i and j;
Q_{ij}	=	water discharge between nodes i and j;
Δt	=	time interval;

w_d	=	settling velocity of particle fraction with diameter d;
Y_i	=	water depth in node i;
m	=	number of nodes connected to node i;
n	=	time increment superscript.

The third term of Equation (1) is the convective term representing the net sediment volume entering or leaving the node i during Δt. The flux concentration is weighted as:

$$c_{ij}^n = ac_i^n + (1-a)\, c_j^n \quad 0 \le a \le 1 \tag{2}$$

The weight coefficients a and (1-a) are interchanged in Equation (2) so that the node supplying the flow has a higher weight.

The fluxes through the links connecting node i to the adjacent nodes, $c_j^n\, Q_j^n$ are compared to those that would result from the application of Toffaleti's (1969) expression for sediment transport. For this, the friction velocity is computed using a gradient equal to the square of the ratio of the computed discharge and conveyance for each link. If the fluxes computed with the existing concentrations are higher than the fluxes computed with the concentrations from the Toffaleti's expression, they are used for the mass balance. Otherwise, they are amended to include such concentrations, as obtained from Toffaleti's expression, which is assumed to be picked up by bottom scour. This will decrease the deposit in node i or may even result in scour from the bottom. The program has a check to make sure that the bottom elevation does not drop below the original bottom elevation, as it is assumed that the present bathymetry represents an equilibrium condition. In cases where bottom elevation drops to the original elevation, the total sediment outflow from the node is assumed to be limited to the sediment volume in suspension and previous deposits. Therefore, the flux concentration c_j^n is recomputed as:

$$c_{ij}^n = \frac{v_i^n\, c_i^n + A_i\, Z_i^n}{\sum_{j=1}^{k} Q_{ij}\, \Delta t} \tag{3}$$

in which Q_{ij}, j= 1,2...., k are only the outflows from the node i, and $A_i\, Z_i^n$ is the volume of previous sediment deposits at the node i, A_i being the surface area and Z_i^n the incremental bed elevation from previous deposits.

The fourth term in Equation (1) represents the volume of deposit in node i, during the integration time interval. A check is made to compare the settling velocity times the integration time interval with the depth. In case the latter is smaller, the deposit is set equal to the total sediment in suspension in the node $v_i^n\, c_i^n$.

The sum of the second and third terms of Equation (1) with their signs changed represents the availability of sediments in the node during the time interval. If it is larger or equal to the fourth term, the difference is used to compute the concentration for the following time interval. If the available material is less than the fourth term, the model assumes that all the available material is settled and the concentration for the following time interval is set equal to zero, $c_i^{n+1} = 0$.

Equation 1 is an explicit solution. The main calibration constant is the time increment (Δt) which must be commensurate with the physical time of particle advection between adjacent nodes. The order of magnitude of such time interval is considerably higher than the order of magnitude of the interval for explicit flow routing. Therefore, flow input for ROUTES must be obtained by averaging output information from LATIS at suitable intervals.

ROUTES OPERATOR'S MANUAL

1. Routes Input File

This file must be created using auxiliary program PREROUT, or a word processor such as Wordstar4 or another editor. At execution time ROUTES prompts for the name of this file, calling it the "input File". Program PREROUT is an interactive program which asks the user a series of questions and builds the ROUTES input file. It is suggested that the user keep this input description handy while using PREROUT.

columns	variable	description
CARD 1		
1-80	TITLE	Any title or other identification for the run (maximum 80 characters). ROUTES automatically labels each run with the names of the input and output files, the date and the time of each run.
CARD 2		
8	IUNIT	0 for English Units, 1 for metric
14-16	NCOR	number of velocity correction links (0 for no corrections required, maximum 100).
24	NTOX	0 for NO THS input, 1 for toxics input file provided (see file description -- 6. THS Concentration File)

columns	variable	description
CARD 3		
6-8	NNODE	number of nodes in the basin, max. 250
14-16	NLINK	number of links in the basin, max. 250
24	ISTRT	starting time step. For the first run of a series which will be restarted, ISTRT = 1. For all non-tidal runs (no restart needed), ISTRT = 0. For a restart run, enter the number of the restart (>1).
25-32	NTIME	last time step of the computation. Generally, this is: $\frac{\text{Total Hours} * 3600}{\text{DT}}$
40	NFR	Number of sediment diameter groups (Must be 5 or fewer in current version)
47-48	NBPT	Number of instantaneous boundary concentrations. ($2 \leq$ NBPT ≤ 10)
55-56	NBN	Number of pollutant source nodes. ($1 \leq$ NBN ≤ 50)
60-64	LMIT	Number of flow data intervals in LATIS input file.
70-72	IIT	Interval of time steps between printing
80	ICON	Flag to indicate the form of the boundary pollutant input. 0 = discharges, 1 = concentrations.
CARD 4		
1-8	DTI	Time interval of input flow from LATIS file (seconds)
9-16	DT	ROUTES computational time interval, seconds
17-24	A	Weighing coefficient of concentration flux. Value ranges from 0.0 to 1.0, the higher value for the supplying node.

columns	variable	description
CARD 4 (cont'd)		
25-32	DDT	Incremental time (seconds) of a tidal cycle beyond (LMIT)*(DTI) (e.g. if the tidal period is 12.42 hours, DDT=0.42 hours = 1512 seconds). Enter 0.0 for non-tidal runs.
33-40	TDF	Water temperature, degrees F.
41-48	VSC5	Kinematic viscosity, 10^{-5} sq.ft./sec
49-56	D65	diameter (mm) of 65 % finer particle
57-64	SPGR	Specific gravity of sediment.
65-72	VCF	Volume conversion factor for LATIS (Usually 1,000,000 for MCM, or 43,560 for acre-feet)
CARD 5		
1-8	DM(1)	Representative particle diameter for sediment size group 1. (mm)
9-16	DM(2)	Diameter for group 2.
17-24	DM(3)	Diameter for group 3.
25-32	DM(4)	Diameter for group 4.
33-40	DM(5)	Diameter for group 5.
CARD 6		
1-8	PC(1)	Percentage of total mass for sediment size group 1. (percent)
9-16	PC(2)	Percent for group 2.
17-24	PC(3)	Percent for group 3.
25-32	PC(4)	Percent for group 4.
33-40	PC(5)	Percent for group 5.

columns	variable	description
CARD 7		
1-8	FLV(1)	Fall velocity for particles from sediment size group 1. (cm/sec)
9-16	FLV(2)	Fall velocity for group 2.
17-24	FLV(3)	Fall velocity for group 3.
25-32	FLV(4)	Fall velocity for group 4.
33-40	FLV(5)	Fall velocity for group 5.

NOTE: Repeat CARDS 8, 9, 10 for each node that is a sediment source. Maximum 50.

CARD 8		
6-8	NODB(j)	Node with sediment source, j.
CARD 9		
1-8	BTIME(j,1)	First instantaneous time of sediment flux, given in CARD 10, emerging from node j (CARD 8). (Minutes)
9-16	BTIME(j,2)	Second instantaneous time.
17-24	BTIME(j,3)	Third instantaneous time (optional).
25-32	BTIME(j,4)	Fourth instantaneous time (optional).
33-40	BTIME(j,5)	Fifth instantaneous time (optional).
41-48	BTIME(j,6)	Sixth instantaneous time (optional).
49-56	BTIME(j,7)	Seventh instantaneous time (optional).
57-64	BTIME(j,8)	Eighth instantaneous time (optional).
65-72	BTIME(j,9)	Ninth instantaneous time (optional).
73-80	BTIME(j,10)	Tenth instantaneous time (optional).

columns	variable	description
CARD 10		
1-8	BQS(j,1)	If ICON = 0, sediment flux from node j corresponding to first time of CARD 9. (cfs or cms)
or		
	BCON(j,1)	If ICON = 1, sediment concentration at node j, first time. (ppm)
9-16	BQS(j,2)	Flux or concentration for second time.
or	BCON(j,2)	
17-24	BQS(j,3)	Flux or concentration for third time.
or	BCON(j,3)	
	•	
	•	
	•	
	•	
	•	
73-80	BQS(j,10)	Flux or concentration for tenth time.
or	BCON(j,10)	

NOTE: The following two cards are only used with NCOR > 0.

CARD 11

6-8	LCOR(1)	First link having a velocity correction factor.
9-16	LCOR(2)	Second link.

NOTE: Repeat, up to 10 links per card, maximum of 100.

CARD 12

6-8	VCOR(1)	Velocity correction factor for first link specified in CARD 11.
9-16	VCOR(2)	Factor for second link.

NOTE: Repeat, up to 10 links per card, maximum of 100.

2. Printed Output File

ROUTES prompts for the name of a new file which will contain the printed output from the run.

3. Latis Input File

When ROUTES prompts for the LATIS input file, enter the full path name of the LATIS output file containing flow and volume values in all links and nodes, listed at desired time intervals during a complete tidal cycle (if applicable). The tidal cycle is selected so that an approximate steady state condition is represented.

If there are no tides in the application, this LATIS output can be as long as necessary. LATIS creates this file automatically when requested. No further editing of the file is required.

4. Restart Output File

This file is automatically generated by ROUTES to make a run for a duration longer than one tidal cycle. The file contains final conditions at the end of one tidal cycle to be used as initial conditions for the next tidal cycle. If no restart is needed, enter ISTRT = 0 in CARD 3 for all runs.

5. Maximum Concentrations Output File

ROUTES prompts for the name of a file in which to store the maximum values of sediment concentrations (mg/1) at each node. If this file is to be imported into LOTUS 1-2-3 for further editing, manipulation, and a display, it must be given a .PRN extension.

If THSs are being modeled, the maximum toxic THS pollutant concentration (ug/1) (greater than zero) is reported in this output file, in records immediately following each node and sediment concentration record. This is the only output for the toxic pollutant concentrations described below.

6. The Concentration File

This optional file contains the THS influx in ug/sec for all nodes that the user cares to define. The user specifies the presence of this file in a ROUTES run by entering a "1" in Column 24 of CARD 2, ROUTES Input file. The file must be created using program LOADS, LOTUS 1-2-3 or an editor such as WordStar.

Each node's input is entered as a group of cards which specify the node number and the toxics influx at the node which will remain constant for the run. Pollutant concentrations will be routed conservatively by ROUTES, using LATIS flows and node volumes.

The input file has the following format:

First Record

Columns 1-4:	Enter the word "NODE"
Columns 8-10:	Enter the node number. ROUTES checks to make sure that this node exists in the LATIS network.

Second Record (repeated for each pollutant, up to 100)

Columns 1-7:	Blank, or the word "TOXIC"
Columns 8-10:	Pollutant identification number. Normally corresponds to the THS Pollutant Codes developed for the Laguna Study.
Columns 11-25:	Pollutant flux at the node, ug/s.

This group of records is repeated for each node the user wishes to provide data for. Pollutants which are not given an initial flux in at least one node are ignored by ROUTES. Output consists of the maximum concentration of each pollutant computed at each node, and is reported in the Maximum Concentration File described earlier.

APPENDIX K-4

DESCRIPTION OF BEACHES

Beach Evolution Caused by Littoral Drift Barrier[a]

By Deva K. Borah,[1] M. ASCE and Armando Balloffet,[2] F. ASCE

Abstract: A numerical model is developed to predict the shoreline changes at Nome, Alaska due to the construction of a causeway that will connect the offshore port terminal with the onshore facilities. The model is based on a procedure developed earlier by other researchers. Several aspects of the original procedure are elaborated and modified. The resultant model was verified by simulating the present beach condition near the entrance jetties of Nome Harbor. Using the same parameters, the model was applied to the causeway and shore configurations for a 30-yr period were predicted. These applications show that the modifications made on the original model are promising. The model can be applied to other similar situations provided the parameters are calibrated by simulating existing conditions.

Introduction

A port to be built at Nome (Norton Sound, Bering Sea, Alaska) will require the construction of a 3,600-ft (1,100-m) long causeway connecting a deep, offshore terminal with the onshore port facilities (Fig. 1). To minimize possible disruption in salmon migration and for easy mobility of small boats, an opening in the causeway with a single span bridge is proposed. To determine the optimal position and maintenance program for the opening and to predict other environmental changes, the littoral drift and changes in the shoreline after construction must be studied.

Fig. 1 also shows the present Nome Harbor, which is protected by two entrance jetties located at the mouth of the Snake River. Each of these jetties is 400 ft (120 m) long. Shoreline on the west side of the west jetty shows evidence of marked accretion. Revetment along the east side of the east jetty is arresting the expected depletion along this side and thus is protecting beach front properties. This indicates that littoral drift prevails at the site from the west, a conclusion that is also supported by others (9–11).

Since the jetties were initially built in the early twenties and were rebuilt with steel and concrete in 1940, the present beach configuration may be considered in equilibrium. Therefore, prevailing littoral drift is at present bypassing the jetties towards deeper water and the eastern beach. This indicates that construction of the new causeway, which is nine times longer than each of the jetties, will introduce major accretion

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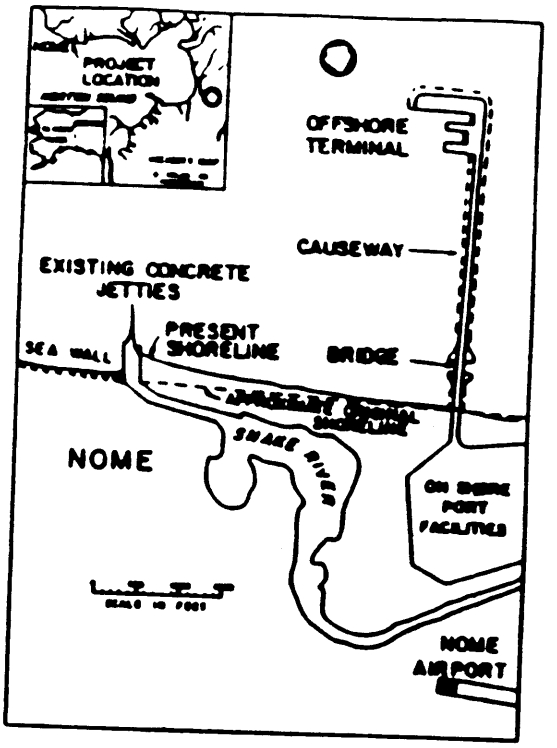

FIG. 1.—Nome Deep-Water Port (1 ft = 0.305 m)

west of the causeway and depletion east of it. Quantitative estimates of these changes must be made for environmental reasons as stated here.

This paper describes the numerical model adopted to predict the shoreline changes, the input data, the data handling procedures, model calibration, and prediction of the continuous changes of shore profiles. Attention is paid in particular to depletion at the downdrift side of barrier and to a procedure to incorporate the effects of diffraction on wave height and breaker angle. Model response to variation of wave parameters is analyzed.

Model Formulation

The model is formulated according to a procedure developed by Le Méhauté and Soldate (7,8). The method is based on studies made to assess littoral phenomena in the Great Lakes, which, as stated by the writers, may be applied to other situations. The beach evolution is studied through analysis of sand flux conservation and its relation with sand storage.

The sand flux is estimated with the use of the standard expression (15) in terms of the wave longshore energy at the beach, which in turn depends on deep-water and breaker angles of the wave crests with the shoreline, and deep-water wave height and period. The expression is written as

$$Q = 7.5 \times 10^3 P_l \quad (1)$$

in which Q = longshore transport rate of sediment in cubic yards per

year, and P_l = linear theory longshore component of wave energy flux in ft-lb/sec/ft of shoreline, given by

$$P_l = \frac{\rho g^2}{64\pi} H_o^2 T K_R^2 \sin 2\alpha_b \quad (2)$$

in which ρ = mass density in lb-sec^2/ft^4; g = gravitational acceleration in ft/sec^2; H_o = deep-water wave height in feet; T = wave period in seconds; K_R = refraction coefficient defined as $(\cos \alpha_o/\cos \alpha_b)^{1/2}$; α_o = angle between deep-water wave crest and shoreline in degrees; and α_b = angle between breaking wave crest and shoreline in degrees. Le Méhauté and Koh (6) approximated the breaker angle, α_b, in terms of the deep-water wave crest angle, α_o, and steepness as

$$\alpha_b = \alpha_o\left(0.25 + 5.5\frac{H_o}{L_o}\right) \quad (3)$$

in which L_o = deep-water wave length in feet given by $gT^2/2\pi$.

Combining Eqs. 1–3, the longshore transport rate can be simply expressed as

$$Q = A \cos \alpha_o \sin z\,\alpha_o \quad (4)$$

in which $A = 15 \times 10^3 \frac{\rho g^2}{64\pi} T H_o^2$ (5)

and $z = 0.25 + 5.5\frac{H_o}{L_o}$ (6)

Fig. 2 shows a schematic representation of the beach evolution model. The beach continuity equation is written as

$$\frac{\partial y}{\partial t} = -\frac{1}{D}\frac{\partial Q}{\partial x} \quad (7)$$

in which y = variable beach distance in yards from the x-axis (x-axis is a reference axis parallel to the average shoreline); D = active beach depth in yards, which is defined as vertical distance between the top of the beach and the lowest line where material is moving; x = distance in

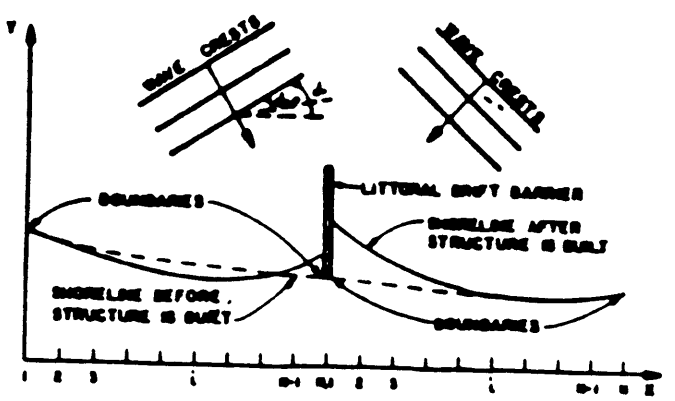

FIG. 2.—Schematic Representation of Beach Evolution

yards along x-axis; and t = time in years.

The shore orientation with respect to the x-axis may be expressed in terms of the wave crest angle with respect to the x-axis, α, and the angle between the crest and shoreline, α_o (Fig. 2):

$$\frac{\partial y}{\partial x} = \tan(\alpha - \alpha_o) \quad \text{(8)}$$

Combining Eqs. 7 and 8 (7,8), a diffusion-type sand flux equation is obtained:

$$\frac{\partial Q}{\partial t} = \frac{\dfrac{dQ}{d\alpha_o}}{D\left[1 + \left(\dfrac{\partial y}{\partial x}\right)^2\right]} \frac{\partial^2 Q}{\partial x^2} \quad \text{(9)}$$

Eqs. 7 and 9 are numerically solved with given initial and boundary conditions to compute the sand flux distribution and the shoreline position at discrete shoreline increments (Fig. 2) and time intervals.

Numerical Solution

The wave climate is specified by the values of α_o and significant H_o and T, which are variables with respect to time. The outer boundaries at both sides of the structure are defined at shore locations where the influence of the structure is negligible. Sand transport rates at these locations are computed from Eq. 1. The other set of boundaries are defined at both sides of the structure itself. For an impermeable structure and if no sand bypassing is allowed, transport rates at the structure is zero. Otherwise, the rates are to be specified. The initial longshore transport rates, before the structure is built, are also estimated from Eq. 1. The initial beach positions, y, are obtained from surveys.

Eq. 9 is rewritten as

$$\frac{\partial Q}{\partial t} = L(t,x) \frac{\partial^2 Q}{\partial x^2} \quad \text{(10)}$$

in which $$L(t,x) = \frac{A(z \cos \alpha_o \cos z\alpha_o - \sin \alpha_o \sin z\alpha_o)}{D\left[1 + \left(\dfrac{\Delta y}{\Delta x}\right)^2\right]} \quad \text{(11)}$$

Eq. 10 is linearized and integrated using a Crank-Nicholson scheme (7,8):

$$\frac{Q_i^{n+1} - Q_i^n}{\Delta t} = \frac{1}{2}\left(L \left.\frac{\partial^2 Q}{\partial x^2}\right|^{n+1} + L \left.\frac{\partial^2 Q}{\partial x^2}\right|^{n}\right) \quad \text{(12)}$$

in which the subscript i represents a space grid point (Fig. 2); the superscript n represents a time grid point; and

$$\frac{\partial^2 Q}{\partial x^2} = \frac{Q_{i+1} - 2Q_i + Q_{i-1}}{\Delta x^2} \quad \text{(13)}$$

Approximating $L_i^{n+1} = L_i^n$ and taking $\lambda = \Delta t/\Delta x^2$, Eq. 12 is simplified to yield

$$a_i Q_{i-1}^{n+1} + b_i Q_i^{n+1} + c_i Q_{i+1}^{n+1} = d_i \quad (14)$$

in which $a_i = c_i = -L_i^{n+1}$ (15)

$$b_i = \frac{2}{\lambda} + 2 L_i^{n+1} \quad (16)$$

$$d_i = \frac{2}{\lambda} Q_i^n + L_i^n (Q_{i+1}^n - 2 Q_i^n + Q_{i-1}^n) \quad (17)$$

Substituting the up- and down-drift boundary transport rates, Q_U and Q_D, Eq. 14 can be expressed as a tridiagonal system and solved using the so-called Thomas or "double sweep" procedure (2). The rates of longshore sediment transport, Q_i^{n+1}, are computed starting from the last node, $i = N, N-1, \ldots, 1$.

Eq. 7 is integrated to compute the new location of the shoreline (y_i, $i = 1, 2, \ldots, N$):

$$y_i^{n+1} = y_i^n - \frac{\Delta t}{2D}\left(\left.\frac{\partial Q}{\partial x}\right|^n + \left.\frac{\partial Q}{\partial x}\right|^{n+1}\right) \quad (18)$$

Computations proceed from left to right on either domain divided by the barrier (Fig. 2). For the left-hand side domain (computations toward the barrier), a backward finite difference scheme is used. Conversely, for the right-hand side domain (computations away from the barrier), a forward finite difference scheme is used.

Influence of Diffraction

The preceding computational procedure is modified to account for diffraction effects in the shadow of the structure, where wave height varies significantly along a wave crest. The refraction coefficient, K_R, is replaced by a combined coefficient, $K_D K_R$, in which K_D = the diffraction coefficient. In addition, the breaker angle, α_b, cannot be expressed by Eq. 3 when diffraction is superimposed to refraction.

Le Méhauté et al. (7,8) derived the following expression for the diffraction coefficient assuming a sinusoidal variation over a distance covering 45° on each side of the geometric shadow from the tip of the structure:

$$K_D(x) = \left[\frac{\sqrt{2}\cos(2\alpha_o)}{2(\cos\alpha_o - \sin\alpha_o)}\right]^{1/2} \sin\left\{\frac{\cos(2\alpha_o)}{4l}\left[x + l\tan(45° - \alpha_o)\right]\right\} \quad (19)$$

in which l = length of the structure. This expression is valid only when the deep-water crest angle, α_o, is smaller than 45°.

Standard diffraction diagrams (15,18) show strong curvature of the K_D isolines in the vicinity of the tip of the structure for a constant depth case. These lines, springing from the tip of the structure, tend to become rectilinear at about 2–3 wave-length distance. Fig. 3 shows a sketch of isoline $K_D = 1$. It can be seen that, for a relatively short structure, its

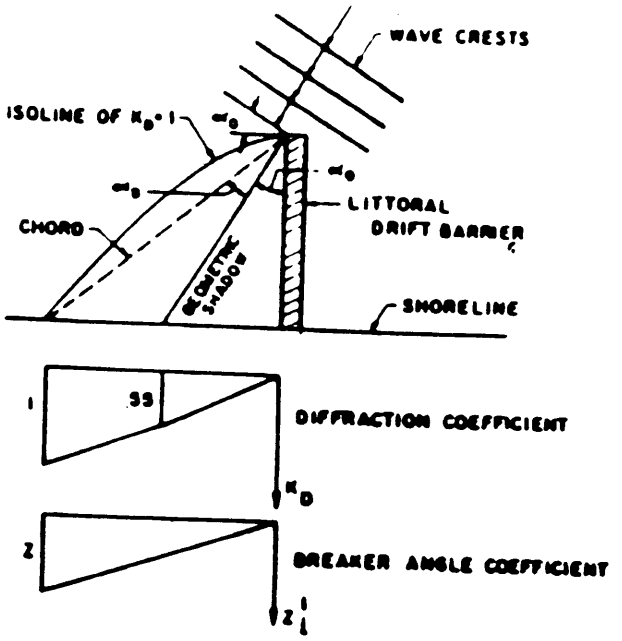

FIG. 3.—Influence of Diffraction and Variation of Breaker Angle

chord would reach the shoreline at a rather wide angle beyond the geometric shadow and that this angle decreases for a longer structure. This would justify the use of a 45° angle beyond the geometric shadow, as in Eq. 19, to determine the limit of variation of K_D only for the case of short structures.

The diffraction diagrams (15,18) show that the geometric shadow is located between the 0.5 and 0.6 K_D isolines. Therefore, in the present study, the diffraction coefficient is assumed to vary linearly from zero, at the toe of the structure, to 0.55 at the geometric shadow, as shown in Fig. 3. It is further assumed to change linearly between 0.55 and 1, the latter value corresponding to the intersection with the shoreline of a ray passing through the tip of the structure and forming an angle of α_0 with the geometric shadow. Based on the aforementioned arguments, this angle is varied from 45° for short structures to 15° for long structures such as the causeway of Nome Deep-Water Port.

The variation of the breaker angle, α_b, in the diffraction zone is accounted by introducing another coefficient, Z_D, at each nodal point, i, within the diffraction zone, which is derived from Eq. 4 and is given by

$$Z_{D_i} = \frac{\sin (z_i'\alpha_o)}{\sin z\alpha_o} \quad \text{(20)}$$

in which z_i' = the value of z at node i. Z_{D_i} represents the ratio between the longshore transport rate at node i and at the node where the diffraction zone approximately ends. It varies from 0–1 from the structure toe, where the longshore transport rate is zero, to the end of the diffraction zone, where the longshore transport rate is given by Eq. 4. Z_{D_i} depends on the value of z_i', which is assumed to vary linearly from 0, at the structure toe, to z (Eq. 6), at the end of the diffraction zone, as shown in Fig. 3. This satisfies the boundary values of Z_{D_i}.

Incorporation of the diffraction coefficient (replacing K_R in Eq. 2 by $K_D K_R$) and the effect of breaker angle variation (Z_{D_i}) into the model are simply made by multiplying the discrete sand flux rate, Q_i^{n+1}, within the diffraction zone, as computed by the aforementioned numerical solution, by $Z_{D_i} K_{D_i}^2$. This procedure simplifies the computations and avoids numerical instability, but it is subject to validation through hindcast of beach history.

Input Data and Parameters

The data required by the model are: structure length, initial beach configuration, active beach depth, and representative time series of wave height, period, and direction.

Wave Data.—The application of the procedure by Le Méhauté and Soldate (7,8) involves consideration of statistical occurrence of waves through conditional probability of heights, periods, and directions from both sides of the structure under study. If wave data are not available, hindcast procedures are used to produce synthetic sequential records from meteorological information. The model incorporates an optional wave hindcast routine. The routine reads historical wind records, speed, and direction, and computes wave heights and periods using the Bretschneider, Reid, Putnam, and Johnson expression [SMB procedure (15)]. A factor, $f = 0.01$, is incorporated to account for bottom friction and percolation. The waves are assumed to progress following the direction of the recorded winds and are directly applied to compute the littoral flux under ideal beach condition sufficiently away from the structure (boundary conditions). The duration of significant wind is assumed equal to the duration of wave activity.

Hindcast waves must be corrected to take into consideration refraction, dispersion in shallow water, and wind duration limitation. This correction should also apply to observed waves depending upon the location of measurements. This is done by simulating the change in beach configuration near an existing structure and applying suitable coefficients to the wave heights used in the littoral drift model. Two different coefficients may be used, one for waves producing littoral drift in one direction along the shore and the other for the opposite direction.

From the preceding wave data, yearly equivalent wave height and period are computed. Wave heights and periods are correlated to eliminate the period from the drift expression given later. Several directions (incident angles) from either side of the structure are alternatively assumed, and the corresponding wave heights (yearly equivalent) are computed by satisfying

$$I \overline{\Delta t}\, \hat{H}_o^2 \hat{T} \cos \hat{\alpha}_o \sin \hat{\alpha}_b = \Sigma(\Delta t\, H_o^2 T \cos \alpha_o \sin \alpha_b) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

in which I = index number of time intervals with wave activity per year from one side of the structure rounded to the nearest integer; $\overline{\Delta t}$ = model time interval ($I\overline{\Delta t} = \Sigma\Delta t$); Δt = duration of each recorded or hindcast wave; $\hat{H}_o$ = equivalent wave height to be computed; $\hat{T}$ = equivalent wave period given by correlation; $\hat{\alpha}_o$ = the assumed equivalent incident crest angle; $\hat{\alpha}_b$ = equivalent breaker angle corresponding to $\hat{\alpha}_o$ (Eq. 3); H_o = recorded or hindcast significant wave height; T = recorded

or hindcast significant wave period; α_o = incident angle with shoreline (from wave direction); and α_b = breaker angle corresponding to α_o (Eq. 3). The quantities within parenthesis in Eq. 21 represent observed or hindcast values and for only one side of the structure. The summation represents summation of the product within parenthesis for one year. Such summations for several years are computed, and their average value is taken. An iterative procedure is used to solve for the equivalent height, $\dot{H}_o$, from one side of the structure. The same procedure is repeated for the other side. The equivalent incident angles, $\dot{\alpha}_o$, are determined by matching the beach configuration near an existing structure. This can simultaneously be done with the preceding wave correction procedure.

Active Beach Depth, *D*.—This parameter is very difficult to measure or estimate. Kraus et al. (5) examined some approximations and expressions of active beach depth adopted by several investigators. These expressions are useful in representing short term variations. They argue that a constant (representative or maximum) depth of closure would be suitable for a long term simulation because of inaccuracies involved in predicting waves over such period. In this model, the beach depth is considered constant for each run.

Program Algorithm

The principal steps used in program BEACHES proceed as follows:

1. Using the beach configuration and fluxes computed in the previous time interval for one drift direction (waves coming from one side of the structure), fluxes for the next time interval are computed (solution of Eq. 14) for the same direction, alternatively using waves determined for each of the assumed incident angles. The fluxes within the diffraction zone are corrected for diffraction and breaker angle variation (Fig. 3 and Eq. 20). Different distributions for fluxes along the shore are obtained from different incident angles. The average of all these flux distributions is used to compute the beach excursion corresponding to the drift direction (Eq. 18).
2. The same procedure is repeated for the other direction, starting again from previous time interval beach position and fluxes for this direction.
3. The resultant beach excursion for the current time interval is obtained by simply superimposing both series of excursions.

Beach Evolution at Nome

Wave Hindcast.—Fig. 1 shows the location of Nome Deep-Water Port. Depths within the Norton Sound are in the order of 50–60 ft (15–18 m), while those between Nome and St. Lawrence Island reach 110–130 ft (33–40 m). Fetches may be considered shallow as regards storm wave generation and are limited by the presence of St. Lawrence Island and mainland shorelines. Substantial energy from outside the window between St. Lawrence Island and the Yukon Delta is dissipated because of refraction toward the Island and the Delta. Also, a number of shoals and islets present in this region break or diffract the waves. Furthermore, wind duration limits the effective fetch for critical waves.

Wave data available when this study was made (11,17) were not considered to be directly applicable to the vicinity of Nome. Therefore, the optional wave hindcast procedure, was used to produce sequential wave data. Three-hour wind records taken at Nome Airport during the years 1965, 1973–1975, and 1979 and for the ice free months (April–November) were used. Only winds from the W through ESE with speeds of more than 8 knots were considered. Wave heights and periods were obtained from the aforementioned routine.

For comparison, wave hindcast was also made by using a more detailed procedure described by Resio (12). Waves were predicted for the months of May–November of 1963, 1968, and 1974, and for the half-plane of waves propagating towards shore. Wave height, spectral peak period, and average wave directions were computed.

Boundary Conditions.—Outer boundary conditions were defined at distances sufficiently far from the structure to avoid substantial error propagation. To represent existing conditions, the sand flux at the jetties was kept zero until the shoreline reached the present position on the west side jetty. Thus, it was assumed that this boundary flux would be equal to the computed flux at sections progressively further away to arrest the displacement of the beach. This was done as there were no expressions to compute the flux for the sand presently bypassing the tip of the jetties and lost to deep water. The presence of the project causeway was simply simulated assuming no sand bypassing. Initial conditions were established by the estimated position of the beach at the construction of the present jetties for model calibration, and the present beach configuration for simulation of the effects of the causeway.

A moderate offshore transport across the beach is also expected because the wave climate at Nome is mostly composed of relatively steep waves. The hindcast waves resulted in values of Dean's parameter (3), $0.6\ H_o g\ T/\pi L_o w$, higher than 1, which corresponds to offshore transport. Here, w = fall velocity of sand particle, a function of sand grain size. This parameter is among the best correlated with transverse littoral drift (13). A fraction of the littoral drift was assumed to be lost due to offshore transport while accounting bypassing in the case of the jetties, as examined earlier.

For the analysis of conditions after causeway construction, attention was paid to a comparison made by Tetra Tech (10) of bathymetric surveys dating from 1900 and 1950, which showed alternate bands of accretion and erosion parallel to shore. Immediately offshore of the Snake River mouth, there was a 2,500-ft (760-m) wide band of accretion and adjacent to it, a 2,000-ft (610-m) band of erosion, followed by a 3,000 to 5,000-ft (910–1,500-m) wide accretion. There appears, therefore, that some offshore transport occurred in the 50 yr intervening between surveys.

The proposed causeway, nevertheless, reaches beyond the nearshore accretion zone and, as will be seen later, the estimated time of arrival of the beach to tip of the structure would be considerably longer than 50 yr. Therefore, this study was made on the assumption of no offshore loss at the structure, which appears conservative, as regards the time of accretion.

Calibration.—Model calibration was done by simulating the observed change in shoreline due to the existing jetties at the mouth of the Snake

TABLE 1.—List of Calibration Runs

Case run (1)	Wave hindcast procedure (2)	Wave Coefficients* c_1 (3)	Wave Coefficients* c_2 (4)	Incident Angles (°) Easterly waves (5)	Incident Angles (°) Westerly waves (6)	Assumed beach depth (ft) (7)	Figure showing results (8)
I	SMB	0.2	0.5	40	30	20	4(*a*)
II	SMB	0.2	0.5	35,40	20,25,30	20	4(*b*)
III	SMB	0.2	0.5	40,40.5,41	20,22.5,25, 27.5,30, 32.5,35	20	4(*c*)
IV	SMB	0.2	0.5	40,40.5,41	20,22.5,25, 27.5,30, 32.5,35	30	4(*d*)
V	SMB	0.2	0.5	40,40.5,41	20,22.5,25, 27.5,30, 32.5,35	10	4(*e*)
VI	Resio	0.2	0.5	40,40.5,41	20,22.5,25, 27.5,30, 32.5,35	10	4(*f*)
VII	Resio	0.11	0.45	40,40.5,41	20,22.5,25, 27.5,30, 32.5,35	10	4(*g*)

*Coefficients c_1 and c_2 are, respectively, for easterly and westerly waves causing westward and eastward littoral drifts.
Note: 1 ft = 0.305 m.

River (Fig. 1). A time interval, $\overline{\Delta t}$, of 360 hr (15 days) and a space increment of 100 ft (30.5 m) were used. Sensitivity runs made varying the time interval showed that 360 hr was satisfactory for the purpose of this study.

Table 1 shows a list of the calibration runs, and Figs. 4(*a–g*) show the results of beach accretion and depletion due to the jetties. Since the jetties are relatively short structures, the diffraction angle beyond geometric shadow, α_D (Fig. 3), was kept constant at 45° in these runs. Wave hindcasts for the runs I–V [Figs. 4(*a–e*)], were made by the optional routine (SMB procedure). Wave heights obtained from this routine were corrected by adjusting the coefficients c_1 and c_2 for westward and eastward littoral drifts, respectively. For a reasonable beach accretion and depletion, values of these coefficients were found to be 0.2 and 0.5 (Table 1). These coefficients were checked by comparing some predicted wave heights and periods with some recorded values obtained in a tide chart taken at Nome on June 24–26, 1981. The band width of the record shows waves of the order of 1 ft (0.3 m) when the recorded wind at Nome was coming from the SW at about 10–12 knots, according to the National Weather Service. The hindcast model without correction would estimate a significant wave height of 2.3 ft (0.7 m) for 10 knots, which implies a correction coefficient of about 0.4. Therefore, the coefficient of 0.5 obtained through littoral drift hindcast was considered adequate.

In the runs I–III [Figs. 4(*a–c*)], the incident angles of waves were ad-

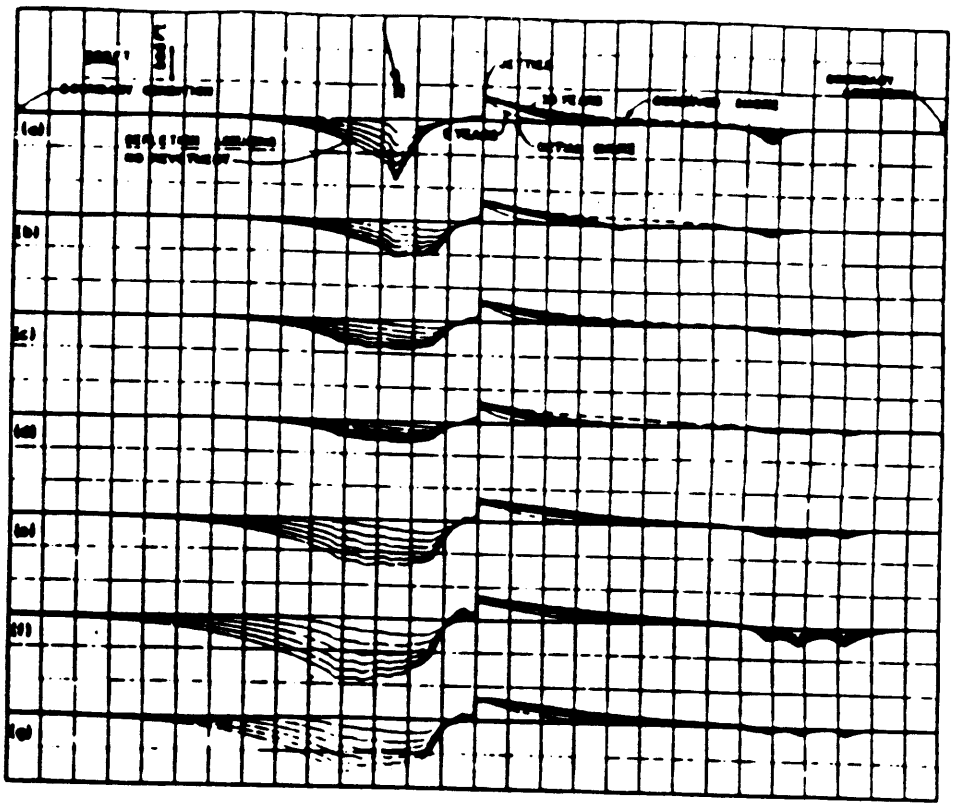

FIG. 4.—Model Verification with Existing Beach Configuration (1 ft = 0.305 m)

justed. The beach depth was kept constant at 20 ft (6 m) during these runs. In run I, single equivalent incident wave from each side of the jetties was used (Table 1). As a result, sharp depletion at each side of the jetties was computed as shown in Fig. 4(*a*). A smoother depletion pattern was obtained by using more than one equivalent wave approach directions and averaging their results, as shown in Figs. 4(*b*–*c*), runs II and III. Finally, in run III, three angles from the east and seven angles from the west were chosen (Table 1).

Next, changes in assumed active beach depth, *D*, were tested. Keeping all other variables same as run III, runs IV and V [Figs. 4(*d*–*e*)] were made after changing the beach depth to 30 ft (9 m) and 10 ft (3 m), respectively. The accretion pattern computed with 30 ft (9 m) beach depth does not match with the observed shoreline, as shown in Fig. 4(*d*), while accretion patterns computed with beach depths 20 ft (6 m) and 10 ft (3 m) produce a better match, as shown in Figs. 4(*c*,*e*). For a mild wave climate, as in the case of Nome, the active beach depth is expected to be moderate. Therefore, an active beach depth of 10 ft (3 m) was considered to be adequate for Nome, and this value was chosen for the beach prediction computations.

Runs VI and VII were made with the waves hindcast by the procedure developed by Resio (12). In run VI, all the parameters, as adjusted earlier, were kept same. This resulted in excessive scour west of the jetties, as shown in Fig. 4(*f*). Consequently, the wave coefficients c_1 and c_2 were changed to 0.11 and 0.45, respectively (Table 1). Run VII was made with the new coefficients. This resulted in an acceptable pattern of scour west

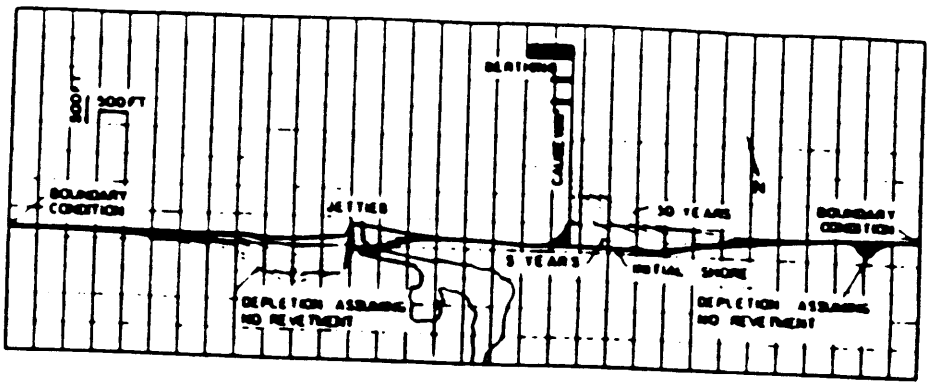

FIG. 5.—Shoreline Prediction near Proposed Causeway (1 ft = 0.305 m)

of the jetties, as shown in Fig. 4(*g*). The difference in the coefficients may be ascribed to the nonlinear nature of the littoral drift response to wave heights (hindcast waves by Resio's procedure were higher than the waves obtained with the SMB procedure).

Finally, runs V and VII made with hindcast waves, respectively by SMB and Resio's procedures, satisfactorily reproduced the present beach conditions west of the jetties [Figs. 4(*e,g*)].

Presently, depletion east of the jetties is prevented by a substantial revetment placed on that stretch of shore.

Shoreline Prediction near Causeway.—The causeway is nine times longer than the jetties, and therefore, angle α_D (Fig. 3) was taken as 15° due to the reasons outlined earlier. The purpose of this study was to estimate the littoral flux arriving at the causeway and the time of arrival of the beach at its location, after construction. Therefore, the model was operated on the assumption that no flux was yet bypassing the structure.

Similar series of model runs, as listed in Table 1, were made with the parameters obtained in the runs made for the jetties. It was observed that the incident angles were less sensitive in a relatively long structure such as the causeway. Fig. 5 shows the shoreline changes near the proposed causeway at a 5-yr intervals, predicted by the model using the hindcast waves by Resio's procedure and with the parameters adjusted for run VII (Table 1).

It is observed that the shoreline will reach approximately 500 ft (150 m) from present shoreline in about 5 yr. If no opening is left in the causeway, the shoreline would reach approximately 1,300 ft (400 m) from present position in 30 yr. Assuming the opening at 500 ft (150 m) from the present shoreline, the shoreline would reach the opening approximately in 5 yr. Based on the 5-yr computed flux at three space increments (300 ft) on the west side of causeway, the probable maintenance dredging is estimated to be about 6,500 cu yd (5,000 cu m) per year.

Fig. 5 shows that, in addition to the accretion on both sides of the causeway, depletion is forecast at the intersections of the shoreline with the geometric shadows of the causeway for the assumed east and west rays. The shapes and locations of these depletion patterns reflect the incremental angles of the rays used in obtaining average incident con-

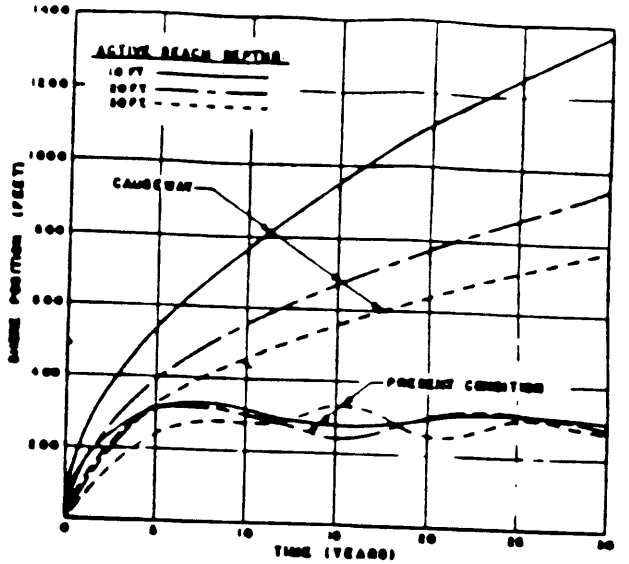

FIG. 6.—Shore Positions at West Side of Structures (1 ft = 0.305 m)

ditions and may be considered qualitative rather than quantitative. It is important to note that depletion on the east side of the causeway will tend to clean the present deposition at the mouth of the Snake River. The depletion computed for the eastern side of the present jetties (Fig. 5) will not occur because of the previously mentioned revetment.

Fig. 6 shows graphs of beach excursion at the structure versus time for present and future conditions. Shuisky and Schvartz (14) and Allison (1) have used exponential expressions, with asymptotes at ultimate configuration, to express beach progression after nourishment operations. The graphs of Fig. 6 do not show an asymptotic trend, for after the construction of the causeway, although the rate of accretion is clearly decreasing. This is due to the fact that the beach is not expected to reach the tip of the causeway within the next 30 yr.

Scour beyond Present Revetment.—Because the littoral flux toward the east will be curtailed by the causeway, scour beyond the present revetment (Sea wall, Fig. 1) may result due to the reduction in the sand flow now bypassing the jetties. The model was applied assuming a rectilinear beach, east of the revetment, and the results are shown in Fig.

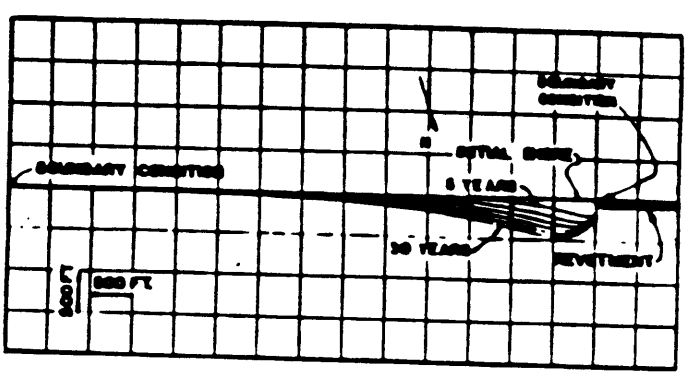

FIG. 7.—Scour beyond Present Revetment, East of Jetties (1 ft = 0.305 m)

7 The boundary fluxes, sufficiently away from the revetment, were assumed same as in the previous cases (Eq. 1). The eastward boundary flux at the end of revetment was assumed one-half of the computed flux (Eq. 1). This value was selected to account for the contributions of the Snake River and the beach at the toe of the revetment. The westward flux at this boundary was assumed constant until the beach retreated a certain distance (100 ft in this run) at this point. Beyond this distance, the flux was assumed zero.

Fig. 7 shows the scour pattern beyond the revetment for a 30-yr period, which is similar to the "crenulate-shaped bay," described by Silvester (16) and Everts (4).

Conclusions

A numerical model was developed in order to predict the shoreline changes at Nome, Alaska due to the construction of a proposed causeway. The causeway will connect the deep-water port terminal with the shore.

The model was based on a procedure developed by Le Méhauté and Soldate. Several aspects of the original procedure were modified. Diffraction zone, as defined by the angle at the tip of the structure, was originally extended from the geometric shadow by a constant angle of 45°. This angle is probably adequate for a relatively short structure, such as the Nome Harbor jetties. In the present model, this angle was varied from 45–15° for a relatively long structure such as the 3,600 ft (1,100 m) long causeway. In addition, a procedure for accounting for the variation of breaker angle within the diffraction zone was incorporated. Originally, statistical occurrence of waves through conditional probabilities of heights, periods, and directions were used. In the absence of wave statistics at Nome, historical wind records were directly entered into the model. The model produced synthetic sequential wave data by using hindcast procedures. These wave data were corrected by using factors to account for the uncertainties of bottom friction, fetch length, and wave directions. These correction factors were verified with available wave data. The model was made more flexible by adjusting the incident wave angles in order to produce the desired distribution of beach accretion and depletion. The beach depth is an unknown parameter, which needs to be determined before the model is applied. All these parameters were determined by applying the model to the Nome Harbor jetties and simulating the present beach condition. Using the same parameters, the model was applied to the causeway and shore profiles for a 30-yr period were predicted.

At present, the wave correction factors, incident angles, and active beach depth are the most sensitive parameters in the model. Range of values of these parameters, as applicable to Nome Beach, are given in Table 1. Accurate wave measurements (height period and direction) and active beach depth estimation would simplify the calibration procedure.

The model can be applied to other similar situations provided the parameters are calibrated by simulating existing conditions. By properly defining the boundary conditions, the model can also be used to reproduce the "crenulate-shaped bays," described by Silvester. More appli-

cation is needed to generalize the range of parameter values. More research is needed to develop relations for offshore transport and transport bypassing the tip of a structure. Further investigations on physically based relationships for the wave breaking angle and its variations under different situations are needed.

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Appendix II.—Notation

The following symbols are used in this paper:

D = active beach depth;
g = gravitational acceleration;
H_o = deep-water significant wave height;
$\hat{H}_o$ = equivalent wave height;
l = index number of time steps with wave activities per year from one side of structure;
K_D = diffraction coefficient;
K_R = refraction coefficient;
L_o = deep-water wave length;
l = length of structure;
P_l = longshore component of wave energy flux;
Q = longshore transport rate of sediment (littoral drift);
T = wave period;
$\hat{T}$ = equivalent wave period;
t = time;
w = fall velocity of sand particle;
x = distance along x-axis;
y = beach locations (distances) from x-axis;
Z_D = coefficient reflecting variation of breaker angle;
α = angle between wave crest and x-axis;
α_b = angle between breaking wave crest and shoreline;
α_D = angle at tip of structure between edges of geometric shadow and diffraction zone;
α_o = angle between deep-water wave crest and shoreline;
$\hat{\alpha}_b$ = equivalent angle between breaking wave crest and shoreline;
$\hat{\alpha}_o$ = equivalent angle between deep-water wave crest and shoreline;
$\underline{\Delta t}$ = duration of each recorded or hindcast wave;
$\overline{\Delta t}$ = model time step;
Δx = space interval; and
ρ = mass density of water.

Subscripts

D = down drift condition;
i = space grid point;
N = last space node point; and
U = up drift condition.

Superscript

n = time grid point.

APPENDIX K-5

WAVE AND WIND DATA USED FOR BEACHES

DAILY AVERAGE WIND AND WAVE NEAR PANAMA CANAL DURING 1984

DAY	ATLAN WIND DIREC	ATLAN WIND SPEED	ATLAN WAVE DIREC	ATLAN WAVE HT	ATLAN WAVE PERIOD	PACIF WIND DIREC	PACIF WIND SPEED	PACIF WAVE DIREC	PACIF WAVE HT	PACIF WAVE PERIOD
1	9.4	0.8	0.0	0.0	0.0	16.7	0.0	0.0	0.0	0.0
2	4.4	1.0	20.0	39.4	8.2	0.0	0.0	0.0	0.0	0.0
3	9.0	0.8	17.3	32.8	15.7	4.7	3.3	0.0	0.0	0.0
4	5.2	0.9	21.7	35.5	12.0	10.0	0.0	0.0	0.0	0.0
5	6.7	0.8	17.5	32.8	10.0	13.3	1.0	0.0	0.0	0.0
6	14.2	1.0	19.7	32.8	10.5	1.0	2.0	0.0	0.0	0.0
7	14.1	0.8	21.5	32.8	8.0	28.3	1.0	0.0	0.0	0.0
8	3.9	0.9	20.0	32.8	9.7	0.0	0.0	0.0	0.0	0.0
9	4.6	0.7	15.0	32.8	9.0	3.0	1.0	0.0	0.0	0.0
10	9.4	1.4	23.3	43.7	17.7	2.0	1.0	0.0	0.0	0.0
11	8.1	1.7	24.3	32.8	13.7	34.0	1.0	33.0	32.8	9.0
12	5.4	1.1	20.0	32.8	13.6	0.0	0.0	0.0	0.0	0.0
13	7.2	1.2	26.7	32.8	10.0	0.0	0.0	0.0	0.0	0.0
14	7.7	1.2	21.0	32.8	8.0	27.6	1.0	33.0	32.8	5.0
15	7.0	1.0	10.0	32.8	19.0	0.0	0.0	0.0	0.0	0.0
16	7.3	1.4	20.5	32.8	13.0	18.5	0.0	30.0	32.8	5.0
17	6.3	1.3	20.0	35.5	14.7	5.0	1.0	0.0	0.0	0.0
18	6.6	1.7	20.0	41.0	14.0	24.7	0.7	23.0	32.8	7.0
19	6.5	1.6	26.0	46.3	14.2	19.0	0.5	0.0	0.0	0.0
20	7.2	1.9	0.0	0.0	0.0	30.5	0.5	0.0	0.0	0.0
21	6.9	1.4	18.0	36.9	9.0	1.0	2.0	0.0	0.0	0.0
22	5.2	1.8	30.0	49.2	11.0	4.0	1.0	0.0	0.0	0.0
23	6.8	1.3	30.0	32.8	19.0	5.0	1.0	10.0	32.8	19.0
24	6.4	1.3	20.0	49.2	9.0	2.0	1.5	10.0	32.8	5.0
25	7.2	1.6	20.0	32.8	15.0	11.7	0.7	0.0	0.0	0.0
26	5.1	1.4	17.1	46.9	10.7	33.0	0.0	0.0	0.0	0.0
27	8.7	2.0	24.3	35.5	11.0	22.5	1.5	0.0	0.0	0.0
28	7.3	2.3	20.0	32.8	11.7	32.0	1.0	0.0	0.0	0.0
29	6.9	1.5	20.0	39.4	11.4	12.3	1.7	13.0	32.8	11.0
30	5.2	1.4	20.0	36.9	10.5	12.0	0.5	0.0	0.0	0.0
31	7.4	1.3	0.0	0.0	0.0	13.3	1.0	31.5	32.8	9.0
32	5.0	1.3	15.0	41.0	13.0	0.0	0.0	0.0	0.0	0.0
33	4.7	1.5	20.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
34	5.8	1.6	0.0	0.0	0.0	18.7	1.0	23.0	32.8	5.0
35	8.0	1.5	0.0	0.0	0.0	27.4	0.8	0.0	0.0	0.0
36	5.8	1.2	0.0	0.0	0.0	23.1	0.2	3.0	32.8	13.0
37	7.7	1.6	20.0	36.1	13.0	11.3	0.3	0.0	0.0	0.0
38	4.3	1.5	20.0	41.0	8.0	36.0	1.0	0.0	0.0	0.0
39	7.4	1.1	3.0	32.8	5.0	16.5	0.5	0.0	0.0	0.0
40	6.3	1.3	15.0	32.8	12.0	13.0	1.0	0.0	0.0	0.0
41	7.1	5.3	30.0	32.8	17.0	4.3	0.7	20.0	32.8	5.0
42	7.4	1.4	0.0	0.0	0.0	27.7	0.0	0.0	0.0	0.0
43	6.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44	7.9	1.3	12.5	45.1	8.5	18.3	0.2	0.0	0.0	0.0
45	8.0	1.3	25.0	32.8	12.0	18.7	0.8	20.0	32.8	19.0
46	7.7	1.0	18.5	32.8	10.5	24.7	1.3	0.0	0.0	0.0
47	5.6	0.7	20.0	32.8	12.5	25.5	0.8	23.0	32.8	13.0
48	9.3	1.0	24.0	32.8	9.8	3.0	0.0	0.0	0.0	0.0
49	8.5	0.9	30.0	32.8	18.3	21.0	0.0	0.0	0.0	0.0
50	8.6	0.9	30.0	32.8	15.7	18.5	1.5	33.0	32.8	13.0
51	6.7	2.8	20.0	32.8	11.0	34.0	0.0	0.0	0.0	0.0

52	8.8	1.3	25.0	41.0	15.0	35.0	0.0	0.0	0.0	0.0
53	8.3	1.6	30.0	32.8	16.0	0.0	0.0	0.0	0.0	0.0
54	5.4	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55	6.7	1.4	20.0	32.8	15.0	6.0	1.0	0.0	0.0	0.0
56	7.1	1.7	26.7	32.8	13.7	0.0	0.0	0.0	0.0	0.0
57	6.8	1.6	0.0	0.0	0.0	19.0	1.5	13.0	32.8	11.0
58	8.4	1.7	10.5	32.8	12.0	0.0	0.0	0.0	0.0	0.0
59	8.5	1.5	20.0	32.8	19.0	3.5	0.0	0.0	0.0	0.0
60	9.7	1.3	20.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
61	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	18.0	1.4	21.0	43.7	10.3	30.7	1.3	0.0	0.0	0.0
64	5.2	1.6	20.0	42.7	11.0	1.7	1.7	0.0	0.0	0.0
65	6.6	1.4	26.7	32.8	16.3	0.0	0.0	0.0	0.0	0.0
66	6.3	1.5	20.0	32.8	17.0	17.5	0.0	0.0	0.0	0.0
67	5.5	2.6	0.0	0.0	0.0	24.7	1.0	23.0	32.8	13.0
68	12.7	1.5	29.0	131.2	13.0	0.0	0.0	0.0	0.0	0.0
69	6.2	1.5	0.0	0.0	0.0	14.5	0.5	0.0	0.0	0.0
70	10.5	1.1	20.0	41.0	14.5	0.0	0.0	0.0	0.0	0.0
71	5.7	1.5	22.0	39.4	13.4	2.0	1.0	30.0	32.8	5.0
72	7.2	1.0	0.0	0.0	0.0	3.0	2.0	10.0	32.8	7.0
73	5.2	1.2	10.0	32.8	11.0	7.5	1.0	0.0	0.0	0.0
74	6.0	1.8	25.0	32.8	17.0	7.0	1.0	0.0	0.0	0.0
75	6.3	1.6	20.0	32.8	10.0	14.5	1.0	0.0	0.0	0.0
76	8.3	1.7	15.0	41.0	14.0	29.0	0.0	32.0	32.8	19.0
77	5.6	1.5	20.0	37.5	13.0	7.0	0.0	0.0	0.0	0.0
78	4.4	1.1	23.3	32.8	10.0	4.7	0.5	0.0	0.0	0.0
79	7.3	1.1	16.6	32.8	11.0	0.0	0.0	0.0	0.0	0.0
80	4.5	0.8	20.0	32.8	7.5	0.0	0.0	0.0	0.0	0.0
81	5.8	0.7	30.0	32.8	11.7	11.0	0.7	33.0	32.8	13.0
82	8.7	1.2	26.7	32.8	13.7	0.0	0.0	0.0	0.0	0.0
83	7.5	0.5	30.0	32.8	15.0	0.0	0.0	0.0	0.0	0.0
84	7.2	1.1	22.9	37.5	13.6	21.5	0.5	33.0	32.8	9.0
85	11.8	1.3	3.0	32.8	7.0	0.0	0.0	0.0	0.0	0.0
86	9.6	0.6	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0
87	9.4	0.9	13.2	32.8	12.0	8.0	1.0	0.0	0.0	0.0
88	9.4	0.7	26.7	32.8	13.0	0.0	0.0	0.0	0.0	0.0
89	8.1	0.6	20.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
90	9.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
91	12.9	0.8	7.7	32.8	8.3	20.0	1.0	0.0	0.0	0.0
92	16.7	0.4	33.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
93	7.7	0.6	24.0	32.8	11.0	12.0	0.5	1.0	32.8	9.0
94	5.9	1.7	30.0	32.8	11.7	19.0	1.0	23.0	32.8	13.0
95	5.1	1.1	20.0	32.8	9.8	21.0	0.0	0.0	0.0	0.0
96	8.4	1.5	28.0	32.8	13.8	15.6	0.4	33.0	32.8	13.0
97	6.6	1.5	17.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
98	9.4	1.4	20.2	36.1	11.4	17.0	0.5	11.0	32.8	9.0
99	6.5	1.1	10.0	32.8	17.0	15.0	0.7	33.0	49.2	7.0
100	6.7	0.8	26.0	32.8	13.0	18.5	1.0	31.0	32.8	19.0
101	6.1	1.0	10.5	41.0	13.0	25.7	0.3	0.0	0.0	0.0
102	6.1	1.3	20.0	49.2	11.0	28.0	0.0	0.0	0.0	0.0
103	9.5	0.9	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
104	9.7	0.1	20.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
105	13.3	0.7	1.0	32.8	5.0	0.0	0.0	0.0	0.0	0.0
106	11.9	1.6	1.0	32.8	5.0	13.0	0.0	31.0	32.8	7.0

107	8.8	1.0	25.0	32.8	15.0	0.0	0.0	0.0	0.0	0.0
108	8.1	1.2	15.0	37.7	14.0	24.0	0.5	12.0	32.8	9.0
109	7.4	0.9	24.6	41.9	8.8	0.0	0.0	0.0	0.0	0.0
110	8.4	0.9	27.3	32.8	14.1	28.2	1.0	13.0	32.8	9.0
111	7.3	1.4	13.2	32.8	9.5	0.0	0.0	0.0	0.0	0.0
112	7.0	1.6	15.0	82.0	19.0	0.0	0.0	0.0	0.0	0.0
113	6.6	1.4	20.0	32.8	19.0	20.0	1.5	0.0	0.0	0.0
114	7.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
115	5.9	1.7	20.0	32.8	9.0	1.0	2.0	0.0	0.0	0.0
116	5.3	1.0	30.0	32.8	10.3	25.0	0.0	0.0	0.0	0.0
117	5.7	0.7	26.7	32.8	8.3	23.4	0.2	0.0	0.0	0.0
118	8.8	0.7	31.0	32.8	5.0	0.0	0.0	0.0	0.0	0.0
119	7.8	1.2	23.3	32.8	13.0	27.5	0.5	2.0	32.8	11.0
120	8.0	0.4	25.0	32.8	10.0	35.0	1.0	33.0	32.8	11.0
121	9.1	0.4	0.0	0.0	0.0	24.0	0.0	0.0	0.0	0.0
122	7.5	1.1	15.7	32.8	12.5	16.0	0.5	0.0	0.0	0.0
123	7.0	1.0	0.0	0.0	0.0	23.5	0.0	21.0	49.2	5.0
124	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
125	5.9	1.5	25.0	32.8	15.0	15.0	0.0	0.0	0.0	0.0
126	6.2	3.0	13.7	32.8	10.3	0.0	0.0	0.0	0.0	0.0
127	7.7	5.6	20.3	43.7	8.3	19.0	0.0	0.0	0.0	0.0
128	8.3	1.5	23.7	32.8	9.7	16.0	1.0	0.0	0.0	0.0
129	6.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
130	7.2	1.1	0.0	0.0	0.0	13.7	0.3	0.0	0.0	0.0
131	7.3	1.9	25.0	32.8	10.0	0.0	0.0	0.0	0.0	0.0
132	6.1	1.7	16.7	32.8	10.3	3.0	1.0	0.0	0.0	0.0
133	9.9	0.8	17.7	32.8	15.0	0.0	0.0	0.0	0.0	0.0
134	10.9	1.1	20.0	49.2	15.7	0.0	0.0	0.0	0.0	0.0
135	6.1	1.4	25.0	41.0	11.0	21.3	0.7	32.0	32.8	15.0
136	5.0	1.3	20.0	32.8	11.0	34.0	0.0	0.0	0.0	0.0
137	4.9	1.6	26.7	38.3	13.0	18.3	1.0	3.0	32.8	7.0
138	6.1	1.1	20.0	32.8	15.0	27.5	0.0	33.0	32.8	11.0
139	8.2	0.6	16.7	32.8	13.0	27.0	0.0	0.0	0.0	0.0
140	6.3	1.1	25.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
141	8.3	1.2	28.0	32.8	11.5	0.0	0.0	0.0	0.0	0.0
142	6.6	1.4	20.0	32.8	13.0	7.0	4.0	0.0	0.0	0.0
143	7.7	1.5	20.0	32.8	12.0	0.0	0.0	0.0	0.0	0.0
144	5.7	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
145	7.1	1.7	25.0	41.0	17.0	33.0	2.0	0.0	0.0	0.0
146	8.4	1.6	23.3	32.8	17.7	0.0	0.0	0.0	0.0	0.0
147	7.0	1.0	23.3	32.8	15.0	0.0	0.0	0.0	0.0	0.0
148	8.5	1.1	20.0	32.8	9.7	0.0	0.0	0.0	0.0	0.0
149	7.5	1.0	20.0	32.8	15.0	14.0	0.0	0.0	0.0	0.0
150	8.1	1.7	30.0	32.8	16.3	22.3	0.7	2.0	32.8	7.0
151	6.9	0.7	30.0	32.8	12.0	16.5	0.5	0.0	0.0	0.0
152	9.6	2.0	20.0	32.8	17.0	22.0	0.0	0.0	0.0	0.0
153	7.9	1.6	20.0	43.7	12.3	21.0	0.5	0.0	0.0	0.0
154	7.7	1.4	20.0	32.8	13.0	15.5	0.0	0.0	0.0	0.0
155	10.1	1.1	20.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
156	9.6	0.8	20.0	32.8	13.8	23.3	0.3	0.0	0.0	0.0
157	19.6	0.9	24.7	65.6	10.3	0.0	0.0	0.0	0.0	0.0
158	12.5	0.2	11.0	98.4	9.0	22.6	0.8	0.0	0.0	0.0
159	12.0	0.7	0.0	0.0	0.0	26.5	1.0	0.0	0.0	0.0
160	7.7	0.8	20.0	32.8	18.0	25.7	0.0	0.0	0.0	0.0
161	6.9	1.0	20.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0

162	7.7	1.0	1.0	32.8	5.0	0.0	0.0	0.0	0.0	0.0
163	10.4	1.2	30.0	32.8	15.0	25.0	1.0	2.0	32.8	11.0
164	8.4	1.0	0.0	0.0	0.0	26.0	0.0	0.0	0.0	0.0
165	10.7	2.4	1.0	32.8	5.0	30.3	1.3	7.5	32.8	8.0
166	7.9	1.8	16.7	29.0	13.0	25.0	0.0	0.0	0.0	0.0
167	8.6	1.8	10.5	36.9	12.0	14.5	3.5	10.0	32.8	9.0
168	9.1	1.1	13.3	22.4	14.3	25.0	1.0	0.0	0.0	0.0
169	6.1	2.1	22.5	32.8	12.5	14.0	0.0	0.0	0.0	0.0
170	13.3	1.6	1.0	32.8	10.0	0.0	0.0	0.0	0.0	0.0
171	5.7	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
172	9.4	1.9	18.5	41.0	10.0	0.0	0.0	0.0	0.0	0.0
173	8.4	2.2	15.0	32.8	15.0	19.3	0.3	0.0	0.0	0.0
174	8.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
175	5.7	1.3	20.0	32.8	5.0	34.0	3.0	13.0	32.8	9.0
176	7.4	1.7	15.0	41.0	10.0	16.0	0.0	0.0	0.0	0.0
177	7.0	1.8	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0
178	4.5	0.5	0.0	0.0	0.0	20.7	0.7	0.0	0.0	0.0
179	7.0	1.4	20.0	65.6	15.0	0.0	0.0	0.0	0.0	0.0
180	9.1	1.3	20.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
181	5.9	1.2	20.0	32.8	9.0	14.5	0.0	0.0	0.0	0.0
182	9.8	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
183	9.8	1.2	23.3	32.8	13.7	28.0	0.0	0.0	0.0	0.0
184	7.6	1.8	21.0	32.8	17.0	22.5	0.0	0.0	0.0	0.0
185	8.1	1.1	0.0	0.0	0.0	32.0	0.0	0.0	0.0	0.0
186	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
187	7.2	1.6	20.0	65.6	16.0	27.2	3.6	0.0	0.0	0.0
188	9.3	1.3	14.4	34.4	14.4	28.6	0.0	0.0	0.0	0.0
189	10.6	1.1	15.0	32.8	14.2	19.7	0.5	2.0	32.8	11.0
190	6.2	1.5	13.3	54.7	14.3	0.0	0.0	0.0	0.0	0.0
191	10.1	0.7	20.0	32.8	17.0	0.0	0.0	0.0	0.0	0.0
192	12.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
193	12.9	0.6	23.3	32.8	15.0	28.0	0.0	0.0	0.0	0.0
194	7.7	2.0	23.0	32.8	9.0	26.0	1.0	0.0	0.0	0.0
195	11.1	1.6	0.0	0.0	0.0	18.0	1.0	0.0	0.0	0.0
196	8.0	1.1	10.0	32.8	19.0	22.5	0.5	0.0	0.0	0.0
197	6.6	0.6	20.0	32.8	9.0	17.0	1.0	2.0	32.8	13.0
198	12.9	0.7	0.0	0.0	0.0	19.0	0.3	0.0	0.0	0.0
199	7.5	0.8	20.0	32.8	12.0	22.8	1.3	23.0	32.8	5.0
200	9.9	1.6	25.5	32.8	9.0	22.0	0.5	0.0	0.0	0.0
201	7.2	2.3	20.0	32.8	17.0	26.6	0.6	33.0	32.8	13.0
202	8.1	0.9	26.7	32.8	15.0	0.0	0.0	0.0	0.0	0.0
203	6.6	1.5	12.7	32.8	17.0	6.0	1.0	0.0	0.0	0.0
204	7.7	1.4	0.0	0.0	0.0	28.0	1.0	0.0	0.0	0.0
205	6.3	1.4	26.7	38.3	12.3	31.5	1.0	7.5	32.8	14.0
206	8.7	1.6	26.7	32.8	16.3	28.0	0.5	17.5	18.0	7.0
207	16.3	1.0	10.0	32.8	15.0	26.0	0.5	0.0	0.0	0.0
208	11.1	0.4	20.0	32.8	13.0	16.0	0.0	0.0	0.0	0.0
209	11.1	0.6	14.3	43.7	11.7	0.0	0.0	0.0	0.0	0.0
210	8.0	1.3	16.7	32.8	14.0	26.0	0.5	0.0	0.0	0.0
211	7.2	1.3	14.0	32.8	14.2	0.0	0.0	0.0	0.0	0.0
212	8.4	1.3	20.7	32.8	9.0	22.5	1.0	0.0	0.0	0.0
213	7.7	1.3	25.0	49.2	17.0	0.0	0.0	0.0	0.0	0.0
214	10.0	0.8	20.0	32.8	17.0	25.0	1.0	0.0	0.0	0.0
215	10.9	1.2	18.0	32.8	11.0	18.8	0.6	12.0	32.8	13.0
216	9.6	1.0	15.5	24.6	12.0	23.7	0.3	0.0	0.0	0.0

217	11.2	0.5	30.0	32.8	13.0	21.0	0.5	21.0	32.8	11.0
218	12.9	0.6	30.0	32.8	15.0	18.0	0.0	0.0	0.0	0.0
219	10.2	1.1	20.5	32.8	17.0	6.0	0.0	0.0	0.0	0.0
220	9.5	1.2	20.0	32.8	16.0	0.0	0.0	0.0	0.0	0.0
221	10.6	1.4	16.7	32.8	13.7	23.2	2.2	22.0	32.8	14.0
222	7.5	1.4	30.0	32.8	13.0	14.3	0.7	0.0	0.0	0.0
223	9.7	1.3	10.0	32.8	14.0	24.5	0.0	32.0	32.8	5.0
224	5.6	2.3	20.0	32.8	10.0	23.7	0.7	2.0	32.8	19.0
225	6.8	1.4	30.0	32.8	18.0	13.5	1.0	0.0	0.0	0.0
226	6.8	1.5	23.3	32.8	15.0	25.0	2.0	2.0	32.8	11.0
227	12.0	1.1	23.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
228	13.3	1.2	1.0	32.8	9.0	0.0	0.0	0.0	0.0	0.0
229	12.1	0.7	21.5	32.8	13.0	24.0	3.5	0.0	0.0	0.0
230	4.9	1.1	0.0	0.0	0.0	29.0	0.0	0.0	0.0	0.0
231	4.6	1.0	20.0	32.8	9.0	33.0	0.5	33.0	32.8	13.0
232	7.1	0.9	10.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
233	10.1	0.9	20.0	32.8	19.0	0.0	0.0	0.0	0.0	0.0
234	8.2	0.6	10.0	32.8	15.0	23.0	0.2	0.0	0.0	0.0
235	13.5	0.5	17.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
236	9.5	0.5	13.2	32.8	15.0	0.0	0.0	0.0	0.0	0.0
237	8.2	1.0	16.2	39.4	15.8	22.6	0.0	0.0	0.0	0.0
238	11.5	1.0	20.0	41.0	10.0	16.0	0.0	0.0	0.0	0.0
239	9.8	1.5	11.5	32.8	12.0	8.0	0.0	0.0	0.0	0.0
240	7.4	1.5	11.0	32.8	6.0	26.0	1.0	2.0	32.8	13.0
241	10.2	1.8	11.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
242	9.2	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
243	7.3	1.4	15.9	37.5	16.4	30.0	0.0	0.0	0.0	0.0
244	7.6	1.5	19.2	32.8	11.9	21.7	0.0	0.0	0.0	0.0
245	10.3	1.5	2.0	49.2	5.0	22.0	0.7	0.0	0.0	0.0
246	7.4	1.0	15.0	32.8	17.0	0.0	0.0	0.0	0.0	0.0
247	10.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
248	7.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
249	13.4	0.6	20.0	32.8	15.0	0.0	0.0	0.0	0.0	0.0
250	11.9	0.6	30.0	32.8	19.0	9.0	0.0	0.0	0.0	0.0
251	8.4	0.3	1.0	32.8	5.0	0.0	0.0	0.0	0.0	0.0
252	8.6	0.7	23.3	32.8	18.3	0.0	0.0	0.0	0.0	0.0
253	4.9	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
254	8.3	1.2	20.2	36.9	12.5	24.0	0.0	0.0	0.0	0.0
255	12.2	0.6	20.0	32.8	19.0	16.5	0.0	0.0	0.0	0.0
256	12.5	2.0	4.3	32.8	8.3	24.7	0.3	2.0	32.8	11.0
257	9.6	0.8	20.2	36.1	17.4	16.0	0.0	21.0	32.8	13.0
258	9.1	0.7	21.0	32.8	5.0	22.7	1.0	0.0	0.0	0.0
259	9.8	1.0	21.0	32.8	7.0	22.0	0.0	0.0	0.0	0.0
260	7.4	0.4	23.3	32.8	15.0	24.5	0.0	0.0	0.0	0.0
261	9.3	1.3	30.0	32.8	19.0	0.0	0.0	0.0	0.0	0.0
262	10.7	1.4	20.0	32.8	13.0	13.3	2.3	1.0	32.8	7.0
263	11.4	1.9	14.2	32.8	17.0	0.0	0.0	0.0	0.0	0.0
264	11.3	0.2	1.0	32.8	13.0	18.3	0.7	11.0	32.8	13.0
265	8.1	0.5	27.3	32.8	12.3	23.0	1.0	2.0	32.8	7.0
266	7.6	0.2	18.2	32.8	10.0	21.0	1.0	0.0	0.0	0.0
267	10.9	0.4	16.0	41.0	16.0	23.0	2.0	2.0	32.8	7.0
268	20.8	0.2	2.0	32.8	5.0	23.0	1.0	0.0	0.0	0.0
269	17.3	0.4	12.0	24.6	6.0	21.0	1.0	0.0	0.0	0.0
270	18.0	0.7	11.0	32.8	13.7	22.7	1.3	0.0	0.0	0.0
271	13.5	0.4	0.0	0.0	0.0	19.7	0.7	22.0	65.6	15.0

272	10.6	0.9	0.0	0.0	0.0
273	16.8	0.8	3.5	41.0	12.5
274	14.4	0.3	33.0	32.8	9.0
275	8.4	0.4	30.0	32.8	16.0
276	6.8	0.8	0.0	0.0	0.0
277	9.3	1.0	20.0	41.0	15.0
278	10.9	0.9	15.0	57.4	17.0
279	0.0	0.0	0.0	0.0	0.0
280	8.9	0.6	30.0	32.8	17.0
281	10.1	1.0	25.5	32.8	14.0
282	6.6	2.0	31.0	32.8	5.0
283	11.6	0.6	0.0	0.0	0.0
284	19.4	0.2	21.0	41.0	15.0
285	10.7	0.3	27.0	32.8	11.7
286	9.9	0.2	25.2	32.8	12.0
287	8.2	0.3	23.2	36.9	10.5
288	12.0	0.5	25.0	32.8	17.0
289	8.2	0.5	30.0	32.8	15.0
290	7.1	1.1	20.0	32.8	10.0
291	8.9	1.5	20.0	32.8	16.0
292	7.6	1.1	30.0	41.0	13.0
293	13.5	0.7	10.0	32.8	19.0
294	7.8	0.9	30.0	32.8	12.0
295	8.5	1.0	10.7	38.3	13.7
296	6.3	1.2	23.3	38.3	11.0
297	6.8	1.0	20.0	32.8	10.0
298	6.5	1.1	0.0	0.0	0.0
299	8.6	1.2	30.0	32.8	15.0
300	7.9	1.3	15.0	32.8	12.0
301	6.5	0.9	30.0	32.8	11.0
302	14.7	1.3	6.5	32.8	13.0
303	7.2	0.9	30.0	32.8	13.0
304	8.9	0.8	15.2	32.8	11.5
305	7.3	0.9	18.9	34.6	13.0
306	8.5	0.8	20.0	76.6	19.0
307	9.7	0.7	20.0	32.8	17.0
308	10.4	0.8	24.3	32.8	14.3
309	6.5	0.9	25.0	32.8	14.0
310	14.2	0.4	17.3	32.8	13.7
311	15.4	0.3	1.0	32.8	11.0
312	19.0	0.7	32.0	32.8	7.0
313	26.0	0.0	23.0	32.8	13.0
314	21.0	0.0	0.0	0.0	0.0
315	13.4	0.1	19.0	32.8	19.0
316	22.9	0.3	10.3	32.0	9.6
317	23.5	0.4	22.0	34.4	15.0
318	26.5	0.8	18.0	32.8	10.5
319	26.2	0.8	10.7	32.8	7.7
320	10.5	0.5	20.7	32.8	9.0
321	17.0	0.5	9.8	32.8	11.0
322	12.9	0.5	18.2	32.8	10.5
323	9.7	0.7	0.0	0.0	0.0
324	4.8	1.3	25.0	41.0	13.0
325	6.5	1.3	30.0	32.8	11.0
326	6.4	2.4	10.0	32.8	11.0

22.0	1.0	0.0	0.0	0.0
24.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
27.0	1.0	2.0	32.8	15.0
24.0	0.3	0.0	0.0	0.0
18.3	1.3	12.0	32.8	7.0
18.5	0.5	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
29.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
22.0	1.0	2.0	32.8	5.0
24.5	0.5	0.0	0.0	0.0
32.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
25.3	0.3	2.0	32.8	15.0
23.0	0.5	32.0	32.8	13.0
27.5	0.0	0.0	0.0	0.0
23.7	0.7	0.0	0.0	0.0
19.0	0.0	0.0	0.0	0.0
30.2	0.6	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
28.5	0.5	27.5	32.8	8.0
29.3	0.7	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
11.0	1.0	0.0	0.0	0.0
28.2	0.5	22.0	32.8	11.0
5.0	0.0	0.0	0.0	0.0
27.0	1.0	32.0	32.8	15.0
25.0	0.5	32.0	32.8	17.0
25.0	1.0	0.0	0.0	0.0
23.5	1.5	27.0	32.8	8.0
20.5	0.0	0.0	0.0	0.0
19.0	1.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
25.3	0.7	32.0	32.8	13.0
22.0	1.0	0.0	0.0	0.0
22.5	0.0	0.0	0.0	0.0
29.0	0.5	0.0	0.0	[illegible]
17.3	0.7	10.5	32.8	[illegible]
24.3	0.3	0.0	0.0	0.0
22.0	1.0	22.0	32.8	5.0
20.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
29.3	0.3	0.0	0.0	0.0
22.0	1.0	0.0	0.0	0.0
22.0	0.0	0.0	0.0	0.0
26.2	0.5	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
23.0	0.0	0.0	0.0	0.0
23.0	0.0	0.0	0.0	0.0
21.0	0.7	0.0	0.0	0.0
19.5	0.0	0.0	0.0	0.0
19.0	1.0	0.0	0.0	0.0

327	11.6	1.6	13.2	36.1	13.4	25.0	0.0	0.0	0.0	0.0
328	10.4	1.4	10.7	32.8	9.7	20.0	1.0	0.0	0.0	0.0
329	9.2	1.2	10.5	32.8	11.0	0.0	0.0	0.0	0.0	0.0
330	7.4	1.8	20.0	32.8	15.0	25.7	0.0	0.0	0.0	0.0
331	7.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
332	6.1	1.5	20.0	32.8	12.7	27.0	0.0	0.0	0.0	0.0
333	4.7	0.6	0.0	0.0	0.0	28.0	1.0	22.0	32.8	12.0
334	27.4	1.2	15.2	32.8	8.5	13.0	0.0	0.0	0.0	0.0
335	20.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
336	23.2	0.9	16.3	32.8	13.0	17.0	0.5	32.0	32.8	5.0
337	11.6	0.4	29.0	32.8	12.5	32.3	1.0	2.5	32.8	14.0
338	9.2	0.4	26.5	32.8	11.0	13.0	1.0	1.0	32.8	7.0
339	10.7	0.5	0.0	0.0	0.0	35.0	1.0	0.0	0.0	0.0
340	6.7	0.7	20.0	32.8	17.0	12.5	0.5	0.0	0.0	0.0
341	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
342	9.9	0.8	30.0	32.8	17.0	22.7	1.0	18.0	32.8	7.0
343	5.5	1.2	30.0	32.8	15.0	31.0	0.7	7.5	38.5	8.0
344	5.6	2.4	0.0	0.0	0.0	29.5	0.5	0.0	0.0	0.0
345	5.9	1.3	30.0	32.8	13.0	25.0	1.0	2.0	32.8	11.0
346	10.0	2.0	15.2	37.7	16.0	0.0	0.0	0.0	0.0	0.0
347	6.7	1.7	17.5	41.0	13.5	9.0	0.0	0.0	0.0	0.0
348	5.1	1.6	21.7	51.9	9.3	0.0	0.0	0.0	0.0	0.0
349	4.6	1.0	0.0	0.0	0.0	6.0	0.7	0.0	0.0	0.0
350	4.9	1.5	23.3	32.8	9.7	35.0	1.0	0.0	0.0	0.0
351	9.6	1.4	2.5	32.8	13.0	0.0	0.0	0.0	0.0	0.0
352	5.4	1.1	10.0	32.8	19.0	0.0	0.0	0.0	0.0	0.0
353	4.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
354	5.5	1.1	20.0	32.8	8.3	32.2	1.2	3.0	32.8	9.0
355	6.6	2.1	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0
356	7.2	2.0	0.0	0.0	0.0	36.0	0.0	0.0	0.0	0.0
357	5.8	1.7	20.0	41.4	12.0	34.0	1.0	3.0	32.8	9.0
358	5.6	1.7	15.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
359	10.4	1.3	23.7	32.8	8.3	13.7	0.7	33.0	32.8	7.0
360	6.6	1.5	30.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
361	7.3	1.3	20.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
362	5.8	1.4	17.5	36.9	13.0	3.2	0.6	30.0	32.8	8.3
363	9.0	1.7	18.0	36.9	12.0	23.7	1.0	0.0	0.0	0.0
364	7.5	1.7	30.0	32.8	15.0	1.0	1.0	0.0	0.0	0.0
365	5.0	2.0	24.0	32.8	10.6	1.5	1.0	0.0	0.0	0.0
366	5.9	2.1	26.7	38.3	11.0	0.0	0.0	0.0	0.0	0.0
367	6.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
368	7.1	2.3	20.0	32.8	11.0	0.0	0.0	0.0	0.0	0.0
369	7.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
370	8.0	2.5	20.0	32.8	13.0	0.0	0.0	0.0	0.0	0.0
371	6.9	2.0	10.0	49.2	17.0	0.0	0.0	0.0	0.0	0.0
372	5.5	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX L

REFERENCE DATA AND REPORTS

APPENDIX L

REFERENCE DATA AND REPORTS

List of Alternatives to the Panama Canal - SINBOL

Contains tabulations of the salient characteristics of the present land Canal and each of the various alternatives.

Data for Future Transportation Systems - SINBOL

Contains some useful tables relating to what is there now. Tables cover vessel sizes, world port characteristics, near-term outlook on new vessels, shipbuilding price trends, operating cost trends, charter rates & relationship between tonnage & L/B/D.

Historical Trade Analysis - SINBOL

Contains historical world ocean trade information and trade routes in relation to the Panamanian Isthmus. Also, recent economic activities of major countries and world, origins and destinations of commodities and recent events affecting the world and regional economy.

Attachment III to the Operating Characteristics and Capacity Evaluation Component Contract

Job Specific Information and Data Pertinent to the Contract. A duplicate of Appendix III of the Inception Report for the Engineering/Cost Component, which is included as information directly applicable to the OCCES component or for reference purposes. It contains the following items:

Item	Description
1	List of Study Cases for Pre-screening
2	Approximate Plans and Profiles
3	Description of Topo Quad Sheets used for Alternative Alignment

Item	Description
4	Approximate Alignment of Canal Alternatives on 1/50,000 topo maps to be purchased
5	Tables of Coordinates of Approximate Alignments of Canal Alternatives
6	Dimensions of Design Ships and Dimensions of Lock Chambers
7	Typical Canal Sections
8	Geology and Slope Stability
9	Conceptual Plan of Sea Level Canal
10	Major Feasibility Check Items
11	Cost and Estimate Schedule Format
12	Capacity of Complimentary Systems
13	Center Port Concept - Executive Summary
14	Design Standards

Data on the Operation of the Panama Canal - D. F. Bastian

Compendium of information on how the Panama Canal is operated at present time, total TICW, water use and modes of operation.

The Transisthmian Alternatives for Increasing the Throughout Across Panama - D. F. Bastian.

A brief description of the various alternatives to be tested.

Panama - A New Set of Locks - D.F. Bastian

A paper presented at the 2nd International Symposium on Coastal Space Utilization, 1991, that discusses double lift and single lift locks.

A New Sea Level Canal Concept - D. F. Bastian

An unpublished paper discussing a sea level canal with currents controlled by locks at the Pacific end.

Annex V - Report of the Interoceanic Canal Study Commission Study of Engineering Feasibility

Contains detailed descriptions of the alternative routes and a comparison of the most promising alternatives - as of 1970.

The Panama Canal Pilot - Capt. George A. Markham

This is a training manual for new pilots, as well as refreshing old pilots.

El Canal A Nivel (Feasibility Study of Vergara Sea Level Canal Proposal) - Por: Ing. D. Vergara Stanziola

Contains information comparing the Vergara Plan with the IOCS 1970 plans and the Lopez-Moreno Plan. Also contains some limited information on construction methodology, ecology and project costs, Pub.: 1982.

El Canal a Nivel (Segundo Tomo) - Por: Ing Vergara Stanziola

Basically a proposal on financing the Vergara Sea Level Canal Project and how the cost may be distributed among the interested parties. Also compares the Vergara Plan with the IOCS plan of 1970 and shows why his plan is more cost affective. Published April 1990.

Handbook of lockage Procedure Locks Division

Panama Canal Commission, Marine Bureau: is issued as a reference and guide for those concerned with the passage of vessels through the locks of the Panama Canal. It outline lockage procedures compiled from existing rules, regulations, orders, established practice and operating experience.

Marine Bureau Operations Manual Section 2. January 1, 1991

Table I - Ship Requirements and Restrictions
Table II - Precautionary Measures due to Cargo

Memorandum, U.S. Government; May 31, 1991

Subject: Information for lockage delays data storage.
A memo explaining how the information collected daily by the three lock control houses is stored, classified and used (five sheets).

Transit Communications Network

A set of seven sheets containing information on how to access the MTCS system.

Miscellaneous sheets

1. a Ship Data bank - Transit Card,
2. a Ship Due Card,
3. and a CANAL TRANSIT TIME Sheet

Tables of Coordinates for the Panama Canal

Different Alternatives
1. Routes 10 and Vergara
2. Third lock, Terminal and variation. Deep Draft, Panamanian Plan
3. Route 14S

The Study of Alternatives to the Panama Canal
Phase I: Preliminary Engineering and cost estimates;
Draft Final Report; November 1991, Yachito Engineering Co., Ltd.
under contract with Japan International Corporation Agency.

This summary Report is a summary of the Interim Report Phase I of the Panama Canal Alternative Study and presents the study results for some of the 36-study cases which have been considered in the first half of Phase I.

The Draft Final Report consists of Part 1-Engineering for Prescreening and Part 2-Cost Estimation for Prescreening.

Draft Final Report; April 1992
Commodity and Traffic Projections Study
The WEFA Group

Contains commodity and traffic projections to years 2020 and 2060.

Information provided by the P.C.C. regarding the "Operational Characteristics and Capacity Analysis" component of the CAS effort. (Received November 12, 1991).

ATTACHMENT A - Contains all ship data bank information for the

Calendar Year 1990. Data has been recorded onto a 20 mb Bernoulli cartridge. It includes the data record layout of the file and photocopies of the Data Processing System Manual sections containing the definitions of the data items.

ATTACHMENT B - Contains the Locks Delay Database for Calendar Year

1990 on a 3½ inch disc along with the data record layout and definitions. Also included are actual locks lanes outages for Calendar Year 1990 and 1991 and proposal lane and culvert outages for Fiscal Year 1992.

ATTACHMENT C - Contains the record of water usage for existing Canal Locks for 1990.

ATTACHMENT D - Contains hydrological information and Data of the Panama Canal Watershed. It comprises seven attachments:

D1. Information on Chagres River discharge rates at different elevations at the gauging station. The table includes information on Chagres, Pequeni, and Boquerón Rivers.

D2. Paper prepared by the Commission's Meteorological and hydrographic Branch on Caño Quebrado River weir site.

D3. Information copied from the Interoceanic Canal Studies of 1970 on the following rivers:

Agua Salud	Frijoles
Mandinga	Chagres
Cuimito	Arrieros

D4. Contains unit hydrographic values for several streams including Chagres and Caño Quebrado. The information was taken from the "Development of Probable Maximum Flood and Review of Flood Routing Procedure" done by the Corps of Engineers in 1979.

D5. Brief summary of major floods in the Chagres River basin since 1879.

D6. Most recent published river data on Chagres, Pequeni, Boquerón, Gatun, Trinidad and Ciri Grande Rivers (1973 - 1978).

D7. Most recent published river data on Chagres, Pequeni, Boquerón, Gatun, Trinidad and Ciri Grande Rivers (1979 - 1983).

ATTACHMENT E - A copy of the summary of the final report from CAORF on their studies of the Panama Canal.