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June 1994

US Army Corps of Engineers
Waterways Experiment Station

Ship Navigation Simulation Study, Grand Haven Harbor, Michigan

by Randy A. McCollum, Larry L. Daggett

WES

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Prepared for U.S. Army Engineer District, Detroit

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Waterways Experiment Station
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Final report

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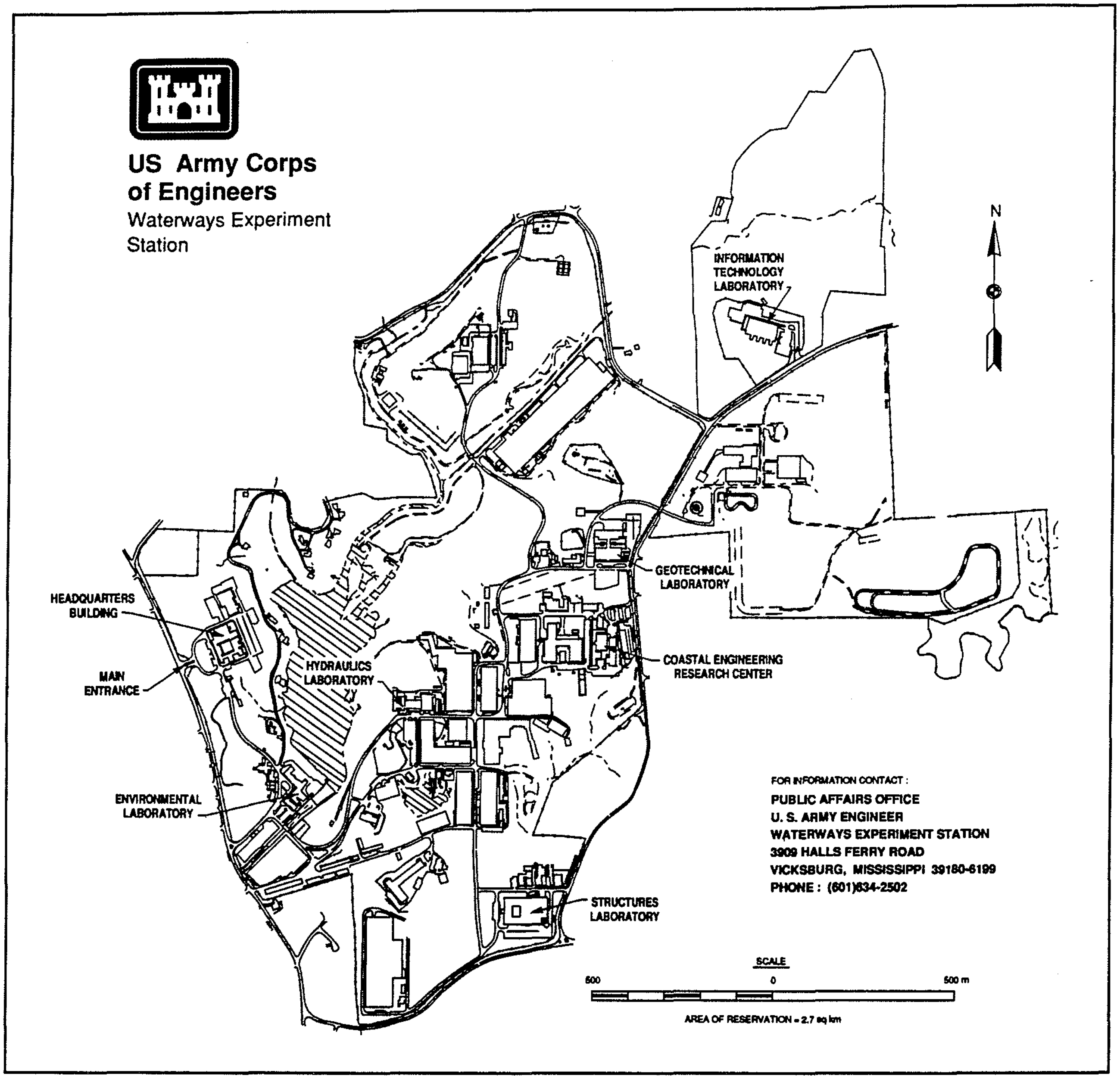

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Contents

List of Figures

Preface

This investigation was performed by personnel of the Hydraulics Laboratory (HL) of the U.S. Army Engineer Waterways Experiment Station (WES) for the U.S. Army Engineer District, Detroit (NCE). This study was conducted with the WES ship simulator during the period January-August 1992. NCE provided survey data of the prototype area. Current modeling was conducted by the Math Modeling Branch, Waterways Division (WD), HL.

The investigation was conducted by Mr. Randy A. McCollum of the Ship Simulator Group, Navigation Branch, WD, under the general supervision of Messrs. Frank A. Herrmann, Jr., Director, HL; R. A. Sager, Assistant Director, HL; M. B. Boyd, Chief, WD (retired); and Dr. Larry L. Daggett, Chief of the Navigation Branch. Ms. Donna C. Derrick, Civil Engineering Technician, Navigation Branch, assisted in the study. This report was prepared by Mr. McCollum and Dr. Daggett.

Acknowledgement is made to Messrs. Dave Wright and Carl Platz, NCE, for their cooperation and assistance throughout the investigation. Special thanks goes to Algoma Central Marine Corporation, Port Colborne, Ontario, Canada, for allowing their pilots to participate in this study.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
horsepower (550 foot-pounds (force) per second)	745.6999	watts
miles (U.S. statute)	1.609347	kilometers
pounds (force)-second per square foot	47.88026	Pascals-second

1 Introduction

Background

Grand Haven Harbor, Michigan, is located on the east shore of Lake Michigan, 108 miles[1] northeasterly from Chicago, IL, and 13 miles south of Muskegon, MI. The U.S. Army Corps of Engineers presently maintains a 300-ft-wide, 21-ft-deep navigation channel from the mouth of Grand River to approximately 2-1/2 miles upstream of the mouth (Figure 1). A turning basin at the upper end of the harbor will allow ships up to 650 ft in length to turn around. Sheet steel revetments protect the shoreline sand dunes on both sides of the river for the lower 4,000 ft and concrete-capped piers (also referred to as jetties or breakwaters) extend about 1,400 ft into Lake Michigan.

The typical ship presently using the channel is approximately 600-750 ft in length. Imported material is mostly coal and slag coming into Verplank Coal and Dock Company near the upper limit of the maintained channel. Export material is mainly sand and gravel being shipped from Construction Aggregates Dock, approximately 2 miles above the mouth.

Proposed Channel Improvements

Proposals to deepen the navigation channel to allow vessels with a deeper draft into the harbor and to provide a new, larger turning basin were stated in a feasibility report issued in 1977[2] (Figure 1). The desired improvements at that time were to deepen the existing navigation channel to a maximum of 27 ft and provide a new, larger turning basin opposite "The Sag."

Since the time of the initial proposals, the U.S. Congress has mandated that local sponsors share the cost of civil projects managed by the Corps. In an effort to hold down the cost of the project, the local sponsor, the city of Grand Haven, and the U.S. Army Engineer District, Detroit, are considering reduction

[1] A table of factors for converting non-SI units of measurement to SI units is found on page v.
[2] U.S. Army Engineer District, Detroit. 1978. "Feasibility Report on Modifications to Grand Haven Harbor, Michigan" (First issued August 1977, Revised June 1978), Detroit, MI.

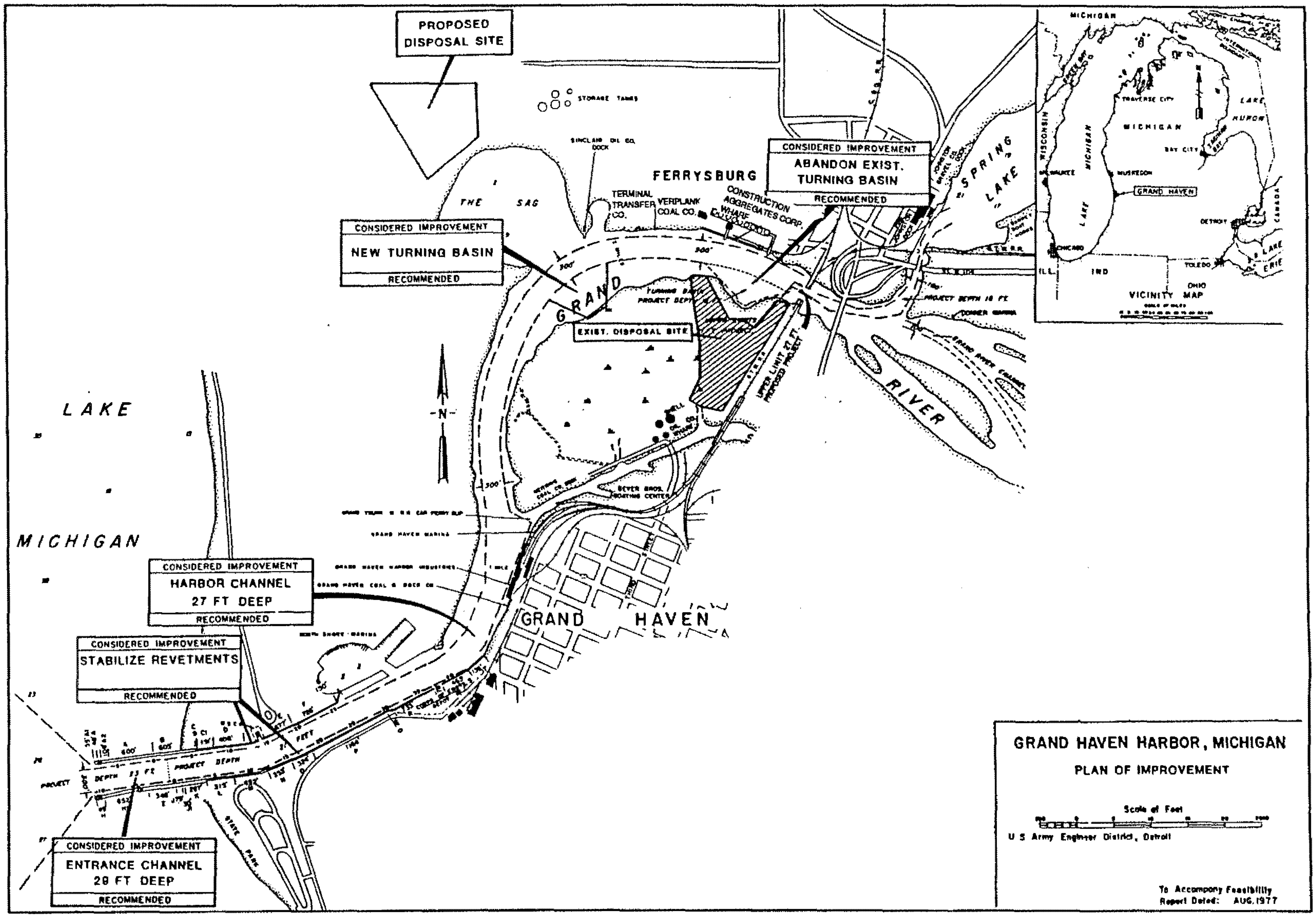

Figure 1. Vicinity and location maps

of the channel width in combination with deepening the channel to reduce initial dredging and annual channel maintenance.

Purpose and Scope of Investigation

The purpose of the ship simulator investigation was to determine the effects of deepening the navigation channel and reducing the maintained channel width on navigation in the channel and to determine the adequacy of and need for the proposed turning basin. Proposed improvements were evaluated by comparing runs made under existing conditions with those made under plan conditions.

The study reach limits of the Grand Haven Harbor simulation were from the railway swing bridge to approximately 1/2 mile out from the ends of the jetties into Lake Michigan (Figure 2). The original study, performed as a "desktop" simulation, included four test plans:

a. 300-ft existing channel, 21-ft depth (base condition) (Figure 3).

b. 225-ft proposed channel, 27-ft depth (Plan 1) (Figure 4).

c. 150-ft proposed channel, 27-ft depth (Plan 2) (Figure 5).

d. Proposed turning basin, 18-ft depth, added to 150-ft proposed channel (Figure 6).

Testing was performed using the U.S. Army Engineer Waterways Experiment Station (WES) portable simulator, which includes only the radar image and precision navigation screen. A total of five shipmasters (one for validation and four for testing) familiar with operation into Grand Haven participated in the tests. Results from this first set of tests were deemed inadequate for final design purposes due to lack of prototype current data and discharge information with which to develop and verify the numerically generated currents, lack of understanding of operational practices of shipmasters in this harbor, lack of experience of the shipmasters in backing into the Grand River and in handling a variety of ship sizes to various terminals in the harbor, and lack of a visual scene of the study area. These tests were valuable in that they proved that the 150-ft channel width proposal was totally inadequate and also yielded possible ways to improve the 225-ft channel design. Due to these factors, the testing was expanded to include a visual scene, testing was scheduled to be performed on the WES ship simulator, and shipmasters were contracted from Algoma Central Marine Corporation to participate in the tests. These shipmasters are thoroughly familiar with backing operations into Grand Haven with the largest ships using bow thrusters. In addition, since it was discovered in the earlier tests that the currents and discharges based on information in a U.S. Coast

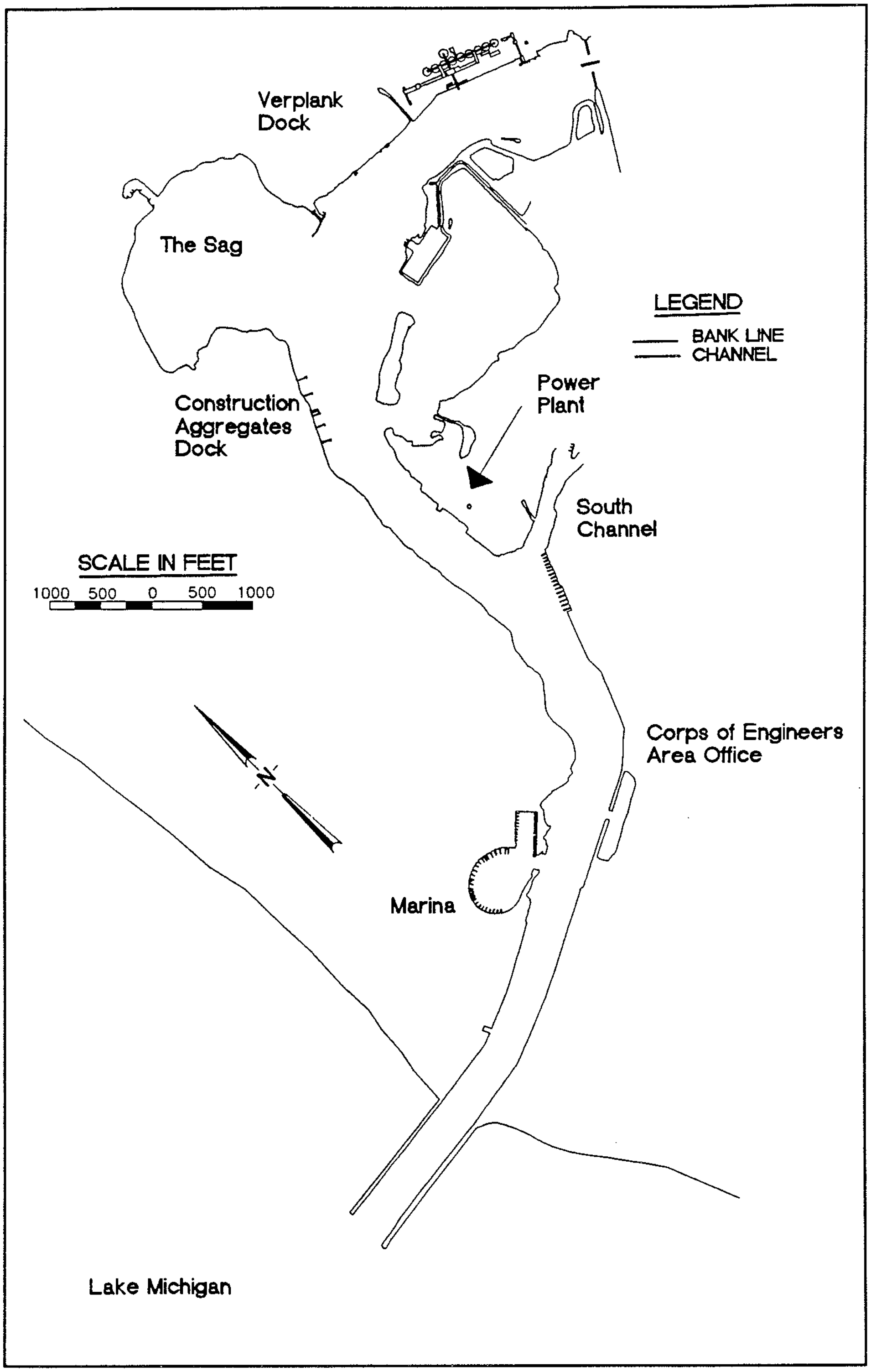

Figure 2. Model test reach

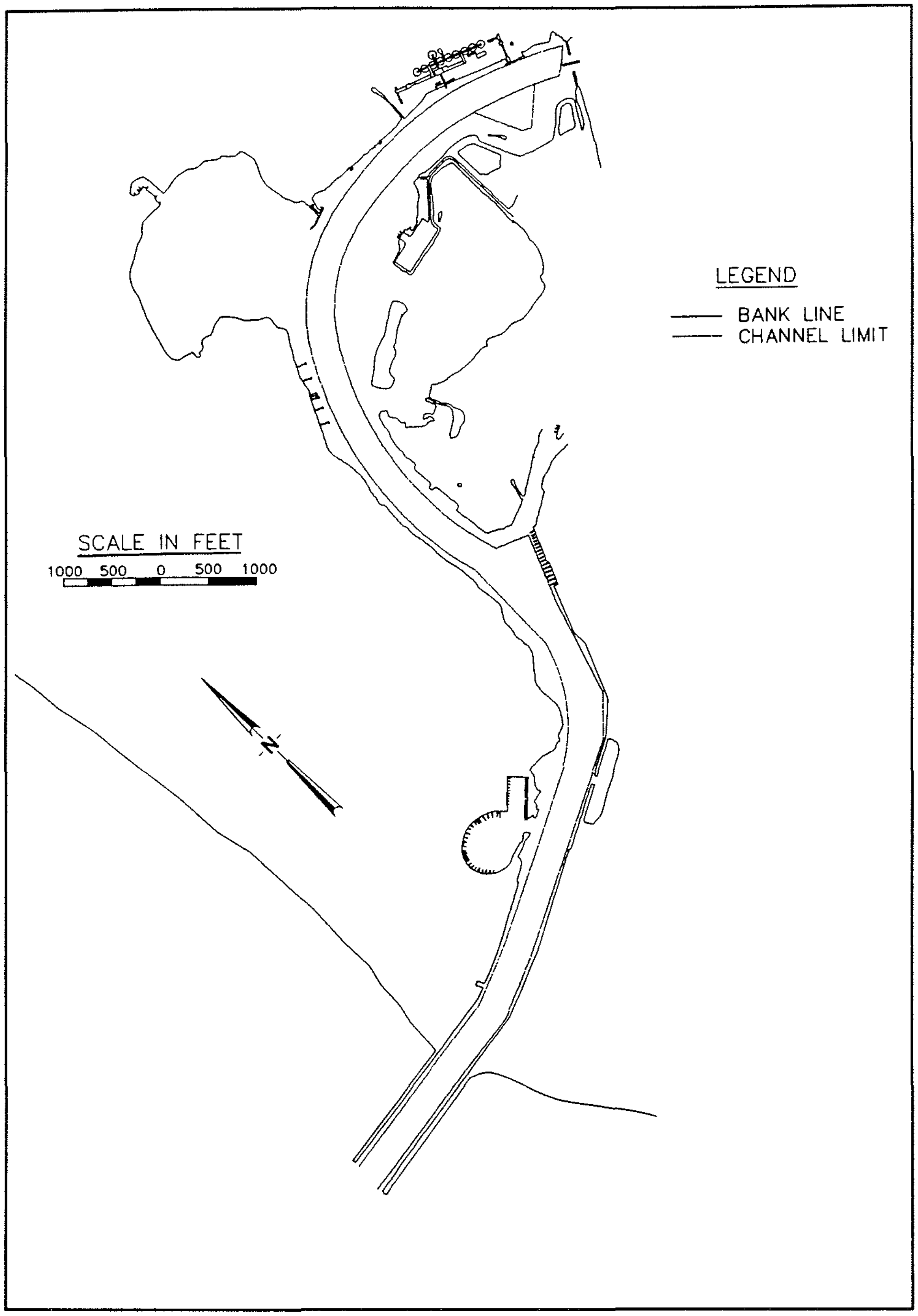

Figure 3. Existing channel (base condition)

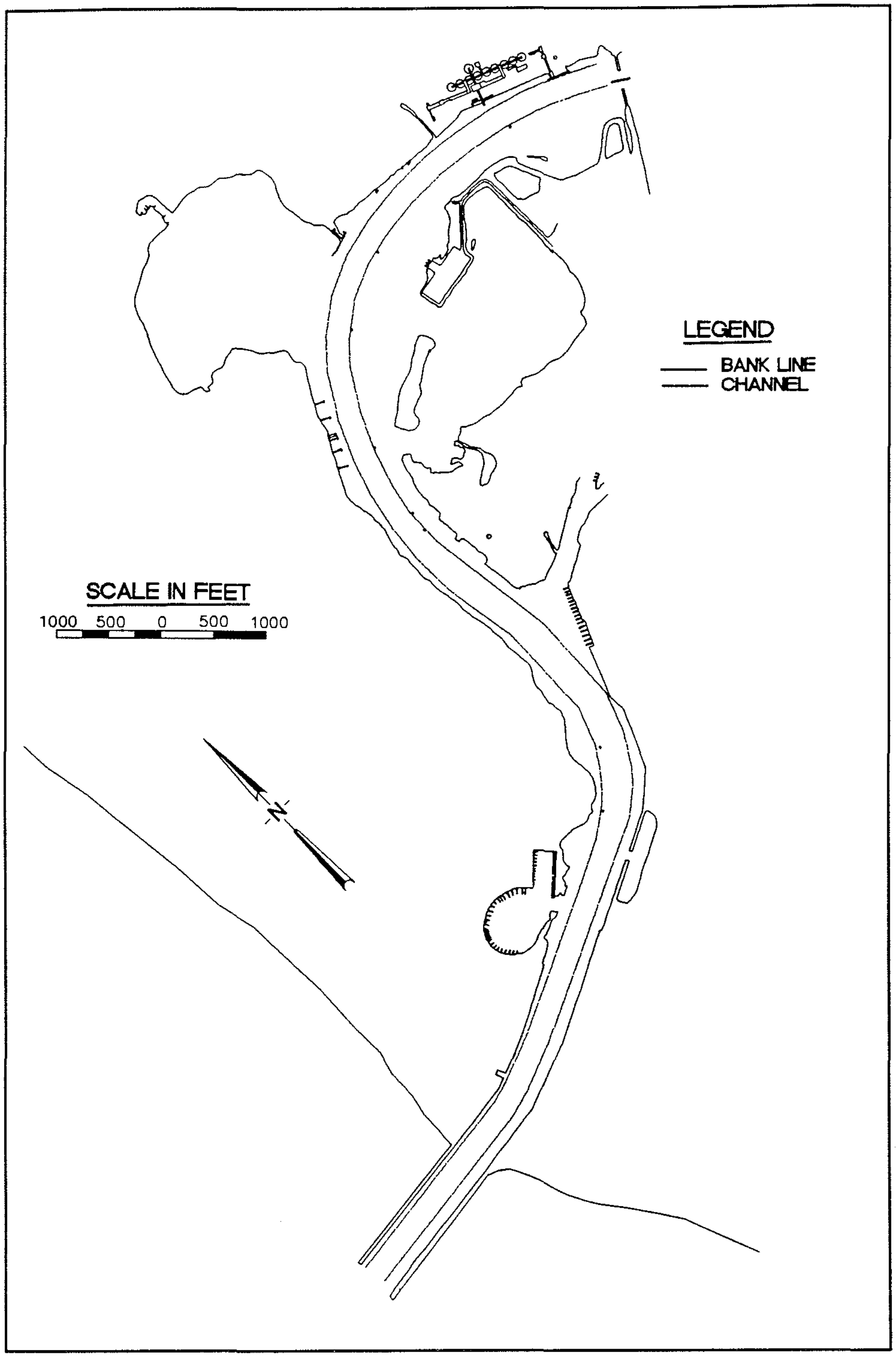

Figure 4. 225-ft proposed channel (Plan 1)

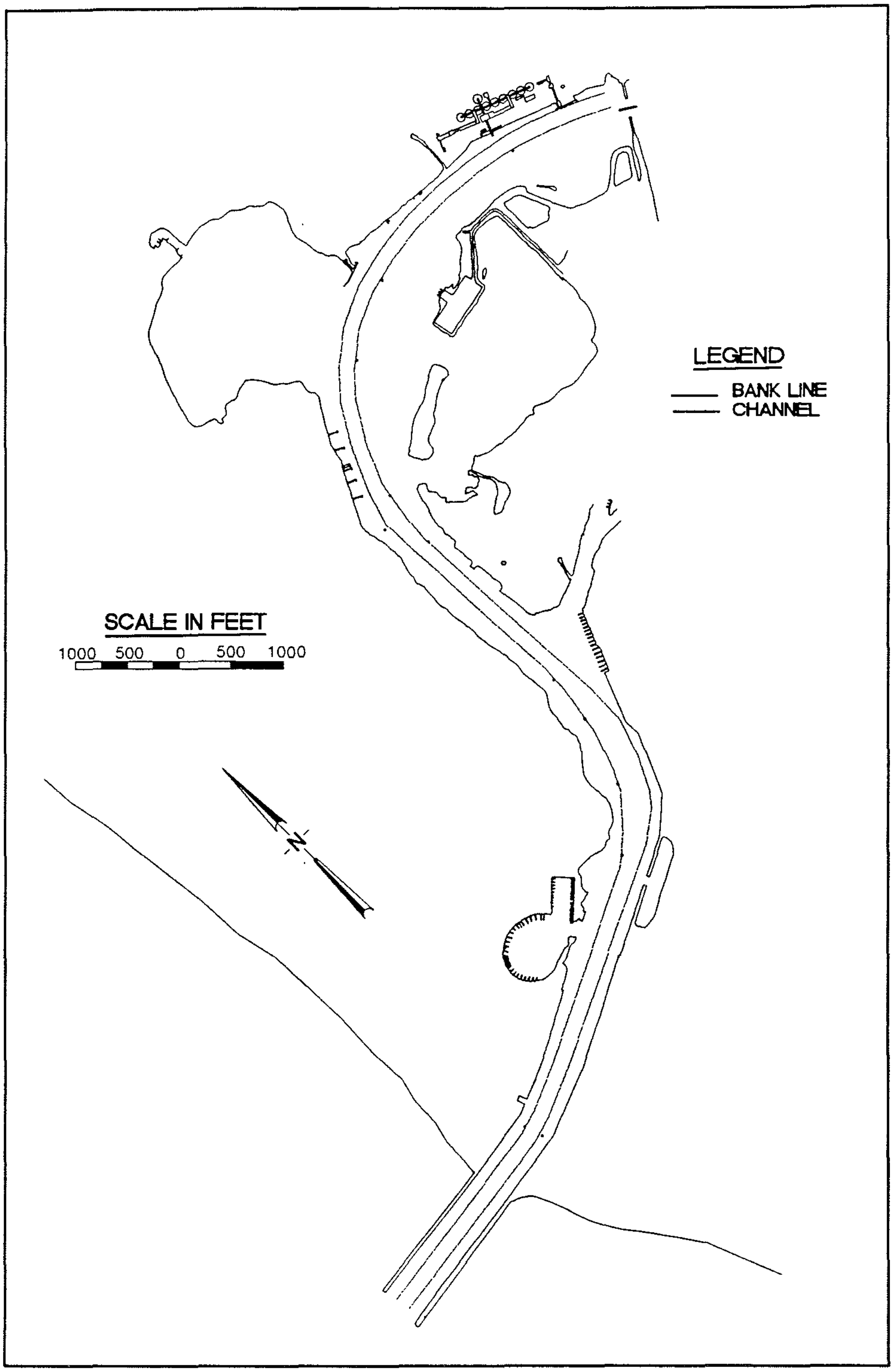

Figure 5. 150-ft proposed channel (Plan 2)

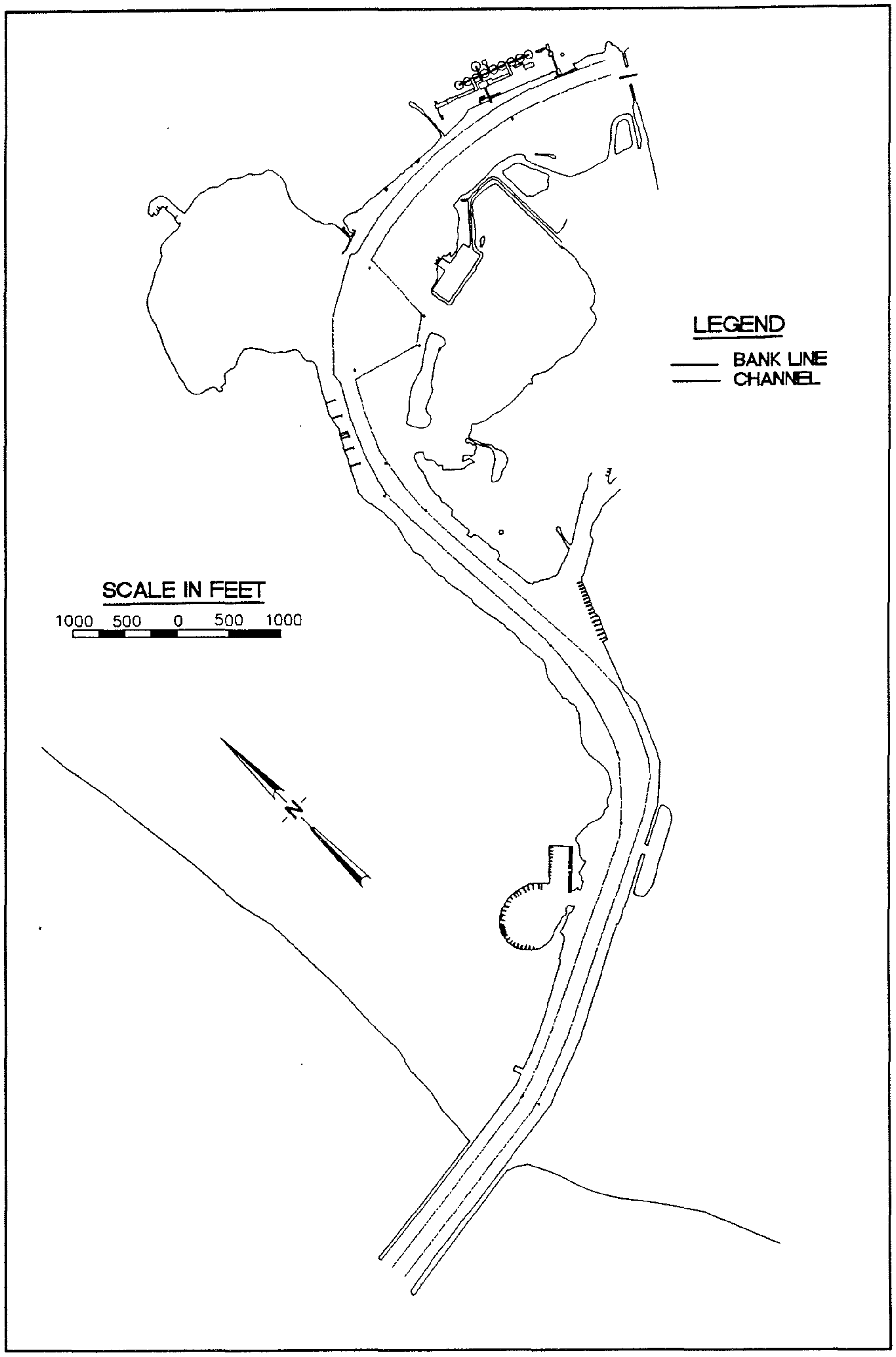

Figure 6. Proposed turning basin

Guard Waterway Analysis Management Study (WAMS)[1] were too high, the currents were recomputed for a lower discharge and reverified.

Because results of the earlier testing indicated that the 150-ft proposed channel was inadequate, this proposal was eliminated. Figure 7 shows the track plots using this channel. The originally proposed 225-ft channel was retained for further study. A modified 225-ft proposed channel was also considered. This plan incorporated improvements to the original 225-ft channel proposal based on the desktop simulation study results. The proposed turning basin was also added to the modified 225-ft channel proposal for further testing. A summary of the plans tested is as follows:

a. 300-ft existing channel, 21-ft depth (Plan 0) (Figure 3).

b. Originally proposed 225-ft channel, 27-ft depth (Plan A) (Figure 4).

c. Modified 225-ft channel proposal, 27-ft depth (Plan B) (Figure 8).

d. Proposed turning basin, 18-ft depth, added to Plan B channel proposal (Figure 9).

The proposed turning basin is not directly linked with any of the channel proposals, but was added to the Plan B channel to test for adequacy of size, location, and need.

[1] Personal Communication, 28 August 1986, from Commanding Officer, USCGC *Acacia*, Subject: WAMS Study of Grand Haven, Michigan Harbor.

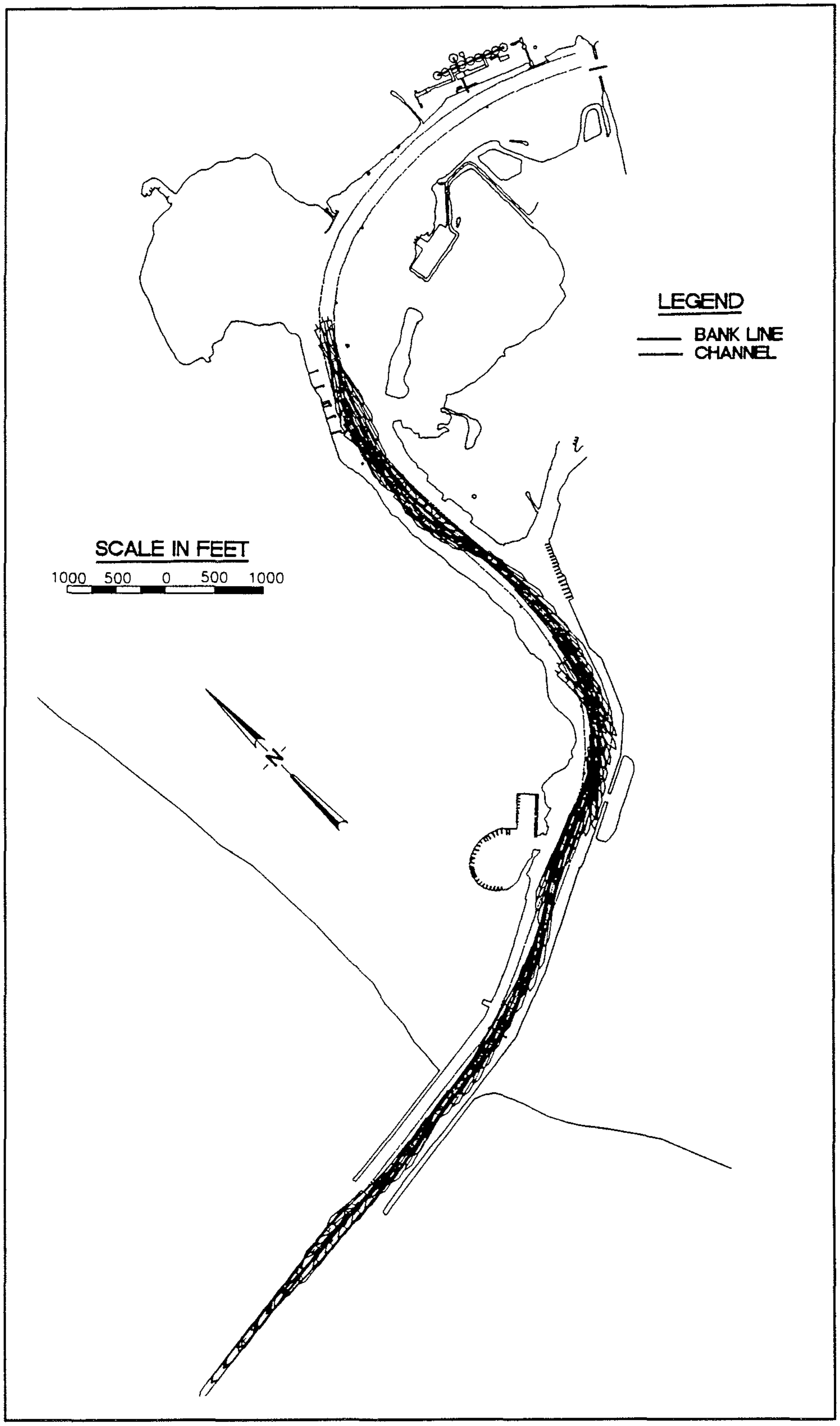

Figure 7. Pilot track plots, 150-ft proposed channel

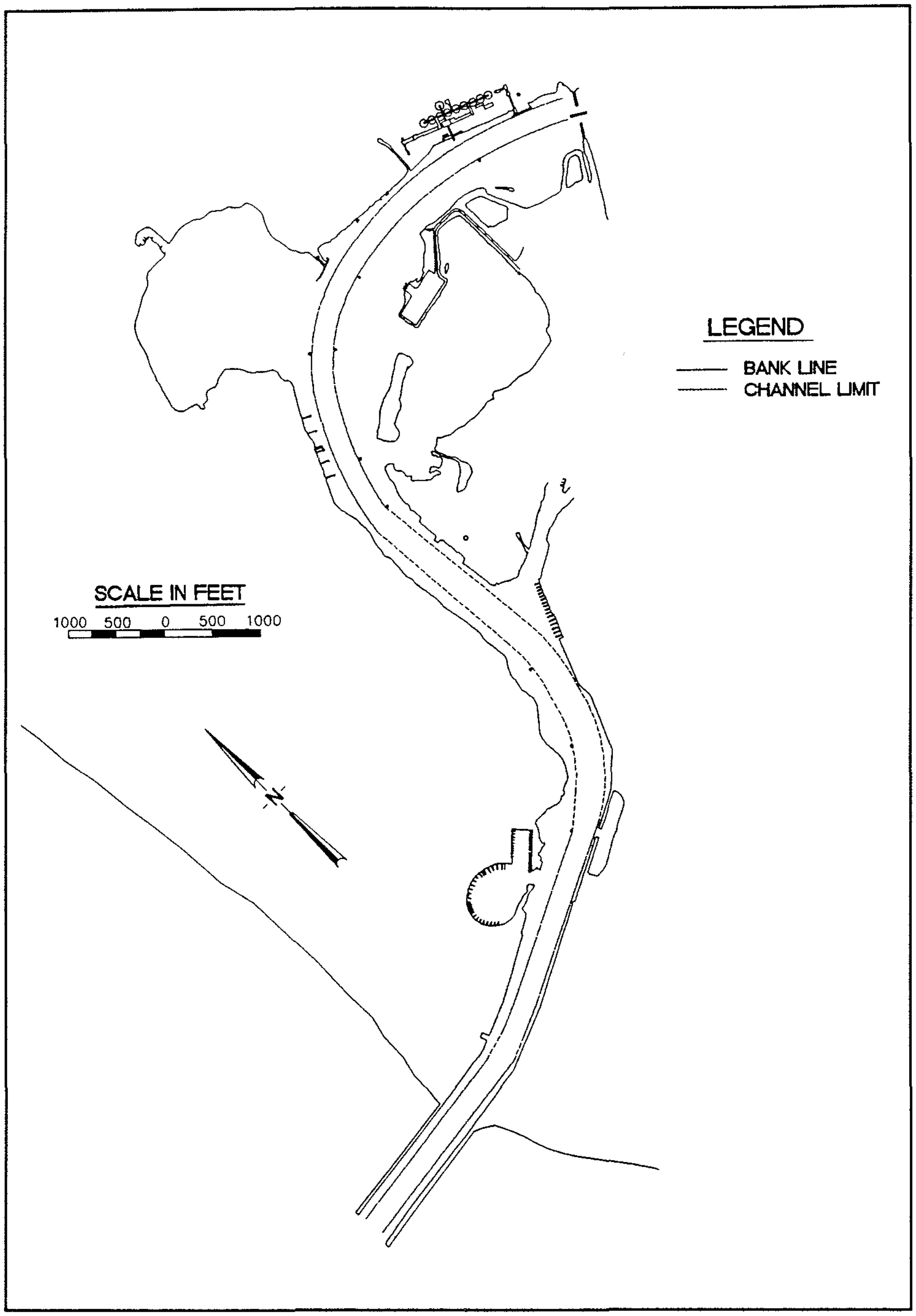

Figure 8. Modified 225-ft channel (Plan B)

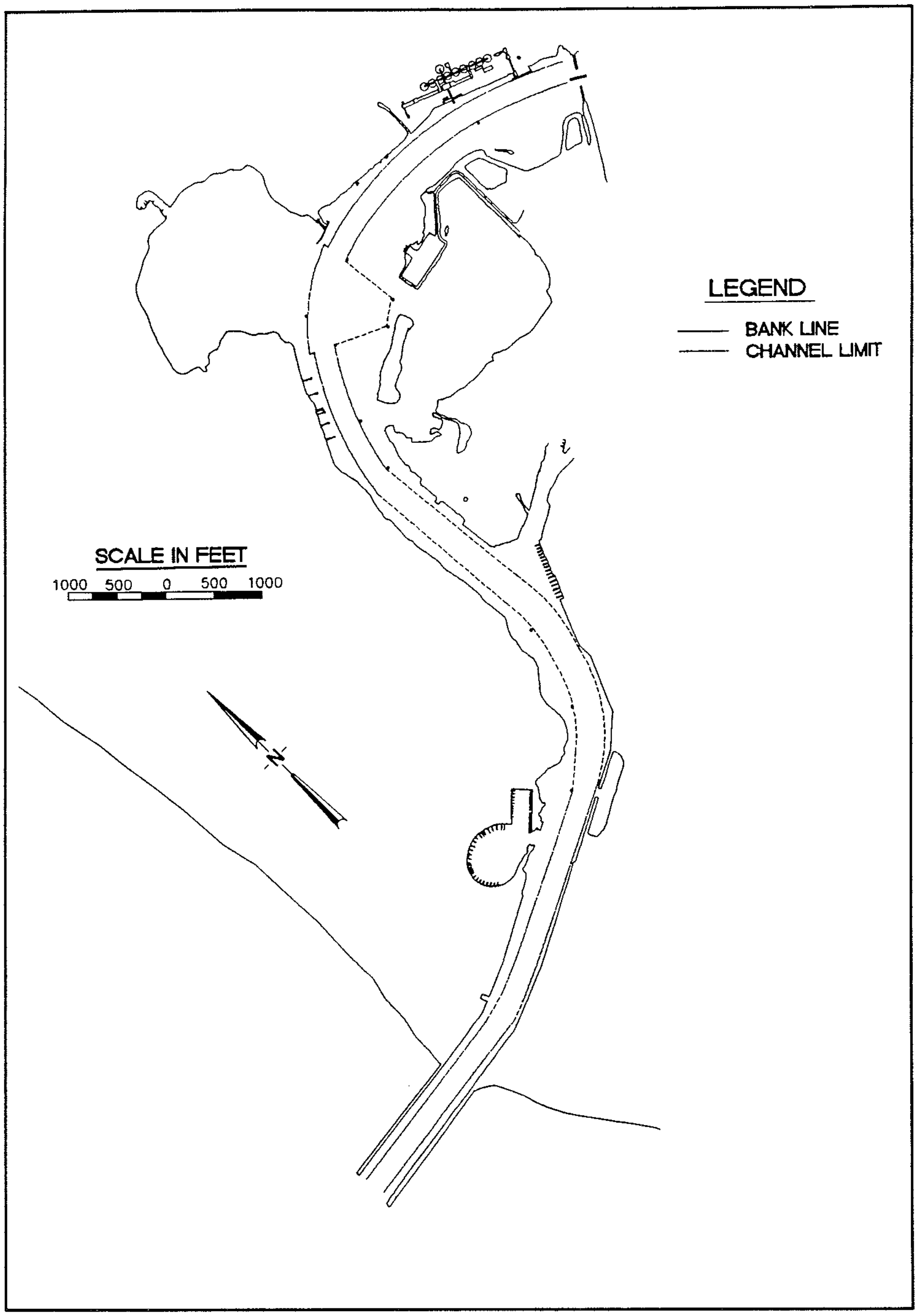

Figure 9. Proposed turning basin

2 Data Development

In order to completely simulate a study area, five types of input data are necessary:

a. The channel database contains dimensions for the existing channel and the proposed channel modifications. It includes the channel cross sections, bank slope angle, overbank depth, initial conditions, and autopilot track-line and speed definition.

b. The visual scene database is composed of three-dimensional images of principal features of the simulated area, including the aids to navigation, docks, and buildings.

c. The radar database contains the features for the plan view of the study area.

d. The ship data file contains characteristics and hydrodynamic coefficients for the test vessels.

e. The current pattern data in the channel include the magnitude and direction of the current and the water depth for each cross section defined in the channel database.

Channel

Channel cross sections are used to define the ship simulator channel database. The information used to develop the channel database came from the District-furnished hydrographic survey charts dated July 1991. This was the latest information available concerning depths, dimensions, and bank lines of the existing channel. State planar coordinates as shown on the hydrographic survey were used for the definition of the databases. Prototype survey ranges were generally used to locate the simulator cross sections. If the prototype survey ranges were not spaced close enough or were not sufficiently oriented, a new range was interpolated. Depths in Lake Michigan were obtained from navigation charts. The mean lake level was set at 578.8[1], based on the National Oceanic and Atmospheric Administration (NOAA) chart number 14933, dated March 1987.

The ship simulator model uses eight equally spaced points to define each cross section. At each of these points, a depth, current magnitude, and direction are required. For each cross section, the width, right and left bank slopes, and overbank depths are required. The channel depth, current magnitude, and direction for each of the eight points was provided by a TABS-2 model, described in the next section.

The channel side slope and overbank depth are used to calculate bank effects on the passing test vessel. The shallower the overbank and the steeper the side slope, the greater the computed bank effects. A small difference (1 to 2 ft) in channel bottom and overbank depth produces negligible bank forces and moments.

Numerical Model Investigation

The two-dimensional numerical model study was conducted using the TABS-2 modeling system.[2] This system provides two-dimensional solutions to open-channel problems using finite element techniques. The system consists of more than 40 computer programs to perform modeling and related tasks. A two-dimensional depth-averaged hydrodynamic numerical model, RMA-2V, was used to generate the current patterns. The other programs in the system perform data management, graphical display, output analysis, and model interfacing tasks.

The computational grid used by RMA-2V was created by a preprocessor code, GFGEN. In addition to a title card and run control data, input to GFGEN consists of an element connection table that identifies the nodes defining each element and a list of x- and y-coordinates and bed elevations for every corner node in the grid. The program then computes coordinates and bed elevations for the midside nodes, computes slopes for all boundary nodes, generates plots of the grid, and writes the binary geometry file used by RMA-2V. For this study, an automatic grid generator was used to create the element connection table and nodal x- and y-coordinates for input to GFGEN. Input to the grid generator consisted of sufficient coordinate locations for the mesh to define the geometry of the study area. Elevation data were obtained from the District-furnished hydrographic survey charts dated July 1991. The program

[1] All elevations (el) and stages cited in this report are in feet referred to the National Geodetic Vertical Datum (NGVD).

[2] William A. Thomas and William H. McAnally, Jr. (1985). "User's Manual for the Generalized Computer Program System: Open-Channel Flow and Sedimentation, TABS-2; Main Text and Appendices A Through O," Instruction Report HL-85-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

then created the element connection table and corner node coordinates as part of the input to GFGEN.

The model study consisted of a base condition and two plans. The base condition grid included a 300-ft-wide channel at el 555.8 referenced to a mean low-water level of 576.8. The base grid consisted of 3,431 elements and 10,678 nodes. The two plan grids incorporated a 150-ft-wide and 225-ft-wide channel at el 558.8. The 150-ft channel grid consisted of 3,328 elements and 10,342 nodes. The 225-ft channel grid consisted of 3,407 elements and 10,584 nodes. Both plans were tested with a turning basin of el 558.8 and without.

For the steady-state flow conditions used in this model study, RMA-2V input consisted of the binary output file from GFGEN, which contains the grid geometry, and the RMA-2V input file. This file consists of all hydraulic parameters required for two-dimensional flow modeling. This file contains the Manning's n values and the turbulent exchange coefficients. The turbulent exchange coefficient of 65.0 lbf-sec/ft^2 was used for all steady-state runs for this study. The Manning's n values used were as follows:

Area	Manning's n
Channel area	0.020
Turning basin	0.020
Bank lines	0.025
Lake Michigan	0.020
Piers and marina	0.040
Marsh area	0.050

Boundary condition types for the hydrodynamic model consisted of a velocity specification of 30,000 cfs at the upstream boundary and a water-surface elevation of 578.8 at the downstream boundary. Land boundaries were given a slip (parallel) flow specification.

Visual Scene

The visual scene database was created from the same maps and charts noted in the discussion of the channel. As in the development of the channel database, the state planar coordinate system was used. Still photographs made during a field reconnaissance trip and comments by local port authorities and Corps of Engineer personnel constituted other sources of information for the scene. These allowed inclusion of the significant features and also helped determine which, if any, features the shipmasters use for informal ranges and location sightings. All aids to navigation such as buoys, buildings, docks, towers, and tanks were included in the visual scene.

The visual scene is generated in three dimensions: north-south, east-west, and vertical elevation. As the ship progresses through the channel, the three-dimensional picture is constantly transformed into a two-dimensional perspective graphic image. This image shows the relative size of the objects in the scene as a function of the vessel's position and orientation and the relative direction and position from the ship bridge for viewing. The graphics hardware used for this project was two stand-alone computers (Silicon Graphics Iris 2400 and Iris 3000) connected with the main computer to obtain information for updating the viewing position and orientation. This information includes parameters such as vessel heading, rate of turn, forward and lateral velocity, and position. Also, the viewing angle is passed to the graphics computers for the look-around feature on the simulator console, which encompasses only a 40-deg field of view. This feature simulates the shipmaster's ability to see any object with a turn of his head. Two graphics computers were used to allow a simultaneous viewing of both the bow and the stern for backing maneuvers without constantly changing the viewing angle. The shipmaster's position on the bridge can also be changed from the center of the bridge to any position wing to wing to simulate the shipmaster walking across the bridge to obtain a better view, e.g., along the edge of the ship from the bridge wing.

Radar

The radar database is used by the radar software to create a simulated radar for use by the test shipmasters. The radar database contains x- and y-coordinates that define the border between land and water. The file also contains coordinates for any structure on the bank or extending into the water such as bridges, docks, piers, and aids to navigation. In short, these data basically define what a shipmaster would see on a shipboard radar. The radar image is a continuously updated plan view of the vessel's position relative to the surrounding area. Three different ranges of 0.5 mile, 0.75 mile, and 1.5 miles were programmed to enable the shipmaster to chose the scale needed.

Current

A current database contains current magnitude, direction, and channel bottom depths at eight points across the channel at each of the cross sections defined in the channel. Interpolation of the data between cross sections provides continuous and smooth current patterns during testing.

Accurate simulation of ship handling in the Grand Haven Harbor channel required detailed modeling of the currents in the channel. Lack of prototype information required that a TABS-2 model study be performed to provide these currents. Current databases were developed for the existing 300-ft channel, proposed deepened 225-ft channel (Plan A), modified 225-ft proposed channel (Plan B), and the proposed turning basin. Maintained channel depths (existing

21 ft and proposed 27 ft) were referenced to the low-water datum for Lake Michigan (576.8 ft). The mean lake level, 578.8, as shown on the NOAA chart for Grand Haven (1987 edition), was a minimum of 2 ft above the low-water datum. The water-surface elevation at the lake was established to be 2 ft above the listed low-water datum, an elevation of 578.8 for the TABS-2 model. This would provide a minimum of 23 ft of depth for the existing channel and 29 ft for the proposed channels. According to information received from the shipmasters, they routinely load their vessels up to 21.5 ft and transit the existing channel.

Test Ship

One design ship was used for shipmaster testing. The vessel required a ship database consisting of the ship characteristics and coefficients used in the ship hydrodynamic model for calculating forces acting upon the vessel. The ship model was developed for a previous model study under a contract with Tracor Hydronautics, Inc.[1]

The design ship used in the simulation was the *A. M. Anderson*, which is 749 ft long, has a 70-ft beam, and was tested with drafts of 18.5 ft (ballasted), 21 ft (existing condition), and 27 ft (plan conditions) with a minimum underkeel clearance of 2 ft.

Wind

Based on conversations with local shipmasters, the dominant wind was determined to be approximately 15 mph from the northwest. Winds of this direction and magnitude occur frequently; and when wind magnitudes exceed 20 mph, the shipmasters usually wait to make their passage. The ship simulator modelled wind as gusting plus or minus 70 percent about the specified 15-mph average. The direction of the wind also randomly varied, with northwest being the predominant direction. Wind effect was constant and was not diminished by natural windbreaks such as topography or man-made objects, such as jetties.

Bow and Stern Thrusters

Based on conversations with local shipmasters, the test vessel was equipped with a bow thruster rated at 850 hp. The thruster could be directed to the right or left, and magnitudes of power could be entered in 25 percent increments

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[1] V. Ankudinov. 1988. "Hydrodynamic and Mathematical Models of Ship Maneuvering Simulations of the Great Lakes Ore Carrier *A. M. Anderson*," Technical Report 87005.0324-1, Tracor Hydronautics, Inc., Laurel, MD.

from 0 to 100 percent. A radar image screen with a range of approximately 0.25 mile was used to indicate magnitude and direction of thrust. A vector from the bow of the vessel indicated direction and the length indicated relative magnitude. As vessel speed increased, the length of the vector decreased as an indicator that thruster effectiveness was reduced. The shipmasters stated that vessels with stern thrusters were not common among Algoma Central's fleet, so a stern thruster was not made available.

3 Navigation Study

Formal shipmaster testing was conducted with two shipmasters from Algoma Central Marine who were familiar with and licensed to operate in the Grand Haven Channel. Involving local professional shipmasters incorporated their experience and familiarity with handling ships in the study area, especially backing into the Grand River, in the navigation project evaluation. The tests were conducted using the WES ship simulator.

The WES ship simulator provides the shipmaster with a helm control, visual references, radar images, and precision navigation parameters such as heading, speed across the bottom, speed through the water, lateral speeds for the bow and stern, wind direction and magnitude, engine revolutions per minute (rpm) setting, and rate of turn, information that he would have on the bridge of a ship. In this study, the shipmasters also served as helmsmen, manning the controls for ship rudder, engine, and bow thruster.

Validation

The following information was verified and fine tuned during validation:

a. The channel definition.

(1) Bank conditions.

(2) Currents.

b. Wind forces.

c. The radar image and visual scene of the study area.

(1) Location of all aids to navigation.

(2) Land/water edge.

The design vessel models for all three drafts had been validated and used in previous simulations at WES.

To validate the reaction of the vessel to bank forces, several simulation runs were made with the vessel transiting the entire study area. The shipmaster gave special attention to the response of the ship to the bank forces. Problem areas were isolated, and the prototype data for these areas were examined. The values for the overbank depth, the side slope, or the bank force coefficient were then adjusted. Additional simulation runs were then undertaken through the problem areas, and if necessary, further adjustment was made. This process was repeated until the shipmaster was satisfied that the simulated vessel response to the bank force was similar to that of an actual vessel passing through the same reach in the prototype.

The reaction of the vessel to current forces was verified by conducting several simulation runs over the entire study area. The shipmaster was instructed to pay particular attention to current effects. The shipmaster was told that the model was set up to have the strongest currents and wind combination that would normally be considered safe for navigation. The currents were modified according to the shipmaster's response until he was satisfied that the currents were reasonably similar to what he had experienced in real life.

Currents developed by the TABS-2 model were based on shipmasters' comments and a U.S. Coast Guard WAMS,[1] which indicated that currents ran up to 3 mph normally and up to 5 mph for short periods after heavy rains. The currents were developed by increasing discharge entering the upper river boundary of the numerical model until a maximum velocity of approximately 4 mph (6 fps) was achieved. The validation of the earlier desktop study had reduced the maximum velocity to 4 fps. New currents generated for this simulation were based on the maximum of 4 fps.

Normally, the simulation is validated by two shipmasters who operate the simulator over a period of from 2 to 5 days, according to the size and complexity of the study; and the previously listed information is adjusted until the shipmaster is satisfied that the simulation is reasonably close to his own experience. Since no prototype current information for the Grand River at Grand Haven exists, current validation was solely dependent on the shipmaster's experience and his interpretation of those currents. In an effort to confirm that the currents used for this simulation would be correct, both shipmasters used for the simulation were allowed to validate the model before they tested. Both shipmasters started with the same currents and bank effects and were allowed to correct each of them until they were satisfied that the simulation was realistic. Bank forces were verified with operations inbound and outbound using both the 21- and 27-ft-draft channels. Currents were verified based on backing upstream into Grand Haven. The validations of the two shipmasters were compared to determine the accuracy of the simulation.

1 Personal Communication, 28 August 1986, from Commanding Officer, USCGC *Acacia*, Subject: WAMS Study of Grand Haven, Michigan Harbor.

Both of the shipmasters believed that the currents generated by the numerical model were too strong, especially for backing into the channel. The currents were reduced and the backing maneuver repeated until the current was judged to be correct. Both shipmasters reached the conclusion that the currents were acceptable at 40 percent of the original values so that the maximum current was approximately 1.6 fps (1 mph). The second shipmaster reached the same conclusion as the first on the currents without knowledge of how the first shipmaster had adjusted them. Current vector plots for the initial currents and the validated currents for all channel conditions are provided in Plates 1-8.

Both shipmasters requested that the bank forces be increased, but they varied on where they required the forces increased. The first shipmaster requested that the bank forces be increased along the entire left descending bank starting just opposite of the Construction Aggregates Dock and going down to the mouth of the river. The second shipmaster requested increases in the bank force for the right descending bank from the Construction Aggregates Dock down to the opposite of the confluence of the Grand and South Channels, on the left descending bank just upstream of the Corps of Engineers Area Office (boat yard), and the right descending bank just below the marina. Bank forces were increased by steepening the angle of bank slope, but all of the bank force increases were relatively small. The differences in where the shipmasters required increased bank forces may be due to the strategies they use in navigating the channel and the position within the channel that they tend to maintain. The validations were judged to be successful and compare favorably with each other even considering the differences in the bank forces for the two validations.

Test Conditions

The Grand Haven Harbor testing schedule as implemented on the WES ship simulator is summarized in the following tabulation.

The proposed 225-ft channel (Plan A) was reduced from the 300-ft existing channel by using the same right descending bank channel edge and taking all the reduction from the left descending bank channel line. This was done due to shoaling along the southern jetty at the entrance to the Grand Haven Channel and also to keep from undermining sheet pile revetments along the waterfront of the city of Grand Haven. Ranges to mark the center of the channel through the jetties were added to this plan due to difficulties experienced by the shipmasters during the desktop simulation study. The modified 225-ft channel (Plan B) used experience gained during the desktop simulation study. The entrance channel was centered between the jetties, the channel was widened toward the Corps boat yard, and the alignment from the city front to Construction Aggregates was straightened and widened compared with the originally proposed 225-ft channel. Since the navigation channel was centered between the jetties for this plan, no ranges were provided. Both 225-ft channel proposals used the right descending channel line of the 300-ft channel from

Construction Aggregates up to the swing bridge because the terminals are on that side of the channel.

Test Channel	Draft ft	Direction	Heading
300-ft existing	21	Inbound	Forward
	18	Inbound	Backward
	21	Outbound	Forward
	18	Outbound	Backward
225-ft proposed	27	Inbound	Forward
	18	Inbound	Backward
	27	Outbound	Forward
	18	Outbound	Backward
225-ft modified	27	Inbound	Forward
	18	Inbound	Backward
	27	Outbound	Forward
	18	Outbound	Backward
225-ft modified with turning basin	18	Outbound	Forward
	18	Inbound	Forward

The condition to be tested (test channel, draft, direction, heading, turn basin) was chosen at random. The chosen condition was then tested and removed from the list of conditions to be tested. This was done to prevent prejudicing the results from overfamiliarity with any one plan condition, for example, all existing conditions being run prior to running the plans. The skill gained at operating the simulator could show the plans to be easier than they really were if all plan conditions were run last. As time permitted, the shipmaster was allowed to repeat a run that was not performed well to see if experience or training could improve the results.

During each run, the characteristic parameters of the ship were automatically recorded every 5 sec. These parameters included the position of the ship's center of gravity, speed, rpm of the engine, heading, drift angle, rate of turn, rudder angle, port and starboard clearances, and usage of bow thruster.

Evaluation of the simulator tests was based on shipmaster ratings, shipmaster comments, average clearance distances, elapsed transit times, and ship track plots. The following chapter will present the methods of analysis for this report.

4 Study Results

Shipmaster Evaluations

After completing each test run, the shipmaster was asked to complete an evaluation of the run, rating the bank effects, current, and ship handling. The ratings for each question for each test condition were averaged, and these averages were plotted in the form of a bar chart to directly rate the same question for each plan condition and operation mode. The plot for the turning basin rates the two operational modes tested: coming inbound, forward into the basin, turning, and coming back to the Construction Aggregates Dock; and backing downstream from Verplank into the basin, turning, and starting downstream bow first. The plots are presented in Plates 9-13.

Inbound, forward

The shipmasters rated all questions (Plate 9) almost identically for each of the channel conditions tested. They rated the Plan B channel to be slightly more difficult than the existing channel and both the Plan B and existing channels to be more difficult than Plan A. This was also true for danger of grounding. Since there were only two shipmasters, the difference in one rating point on the questionnaires is one-half point on the average plotted on the bar chart; therefore, the rating differentials are not statistically significant.

Inbound, backing

The shipmasters rated both the plan conditions to be higher in difficulty than the base condition by a significant margin, even though they rated the attention required and danger of grounding to be the same for all three conditions (Plate 10). The shipmasters also rated the Plan B channel higher in all the other questions than either Plan A or the existing channel. The large disparity between ratings of bank effects is due to one shipmaster rating the bank effects as 0 for the existing condition. He possibly misunderstood the question, since he rated only one other question for any other run less than a 7. Averaging the 0 with the other shipmaster's rating of 7 for that question made the average very low. For the Plan A channel, one shipmaster failed to put any rating on that particular question, so the value plotted is the actual rating by the other shipmaster. If the shipmaster had rated the question, the average could have been much higher than the single rating. The rating values for the bank effects should be discounted due to these anomalies.

Outbound, forward

Plan A was rated slightly higher in difficulty and danger of grounding than either of the other two test conditions (Plate 11). For most questions, Plan B was rated the same as or slightly less than the existing channel.

Outbound, backing

Plan B was rated higher in difficulty and in danger of grounding than either the existing or Plan A channels (Plate 12). The large disparity in ratings for bank effects on the ship is not easily explainable. For the existing channel, both shipmasters rated the effects as moderate. For Plan A, they both rated the effects as very high, even though the channel was deepened to 27 ft and the vessel was drafting 18.5 ft. For Plan B, one shipmaster rated the effect as 1, or very low, and the other rated it at 8, or very high. This channel was also 27 ft deep and used the 18.5-ft-draft vessel. The shipmaster who rated the bank effect high made the transit much faster than the other shipmaster. Generally, the higher the vessel speed, the stronger the bank forces will be. This may account for the large differential of the shipmasters' ratings for this question.

Turning basin runs

The ratings on all questions for backing down from Verplank and turning are the same as or higher than those for coming upstream forward, turning, and coming back down to Construction Aggregates (Plate 13). The high values for difficulty of run, attention required, and danger of grounding are probably due to the shipmasters having to turn in a "floating" position. In normal practice, the bow would rest on the bank and the vessel would pivot about the bow. The simulation did not provide a "solid" bank for this maneuver; therefore, they were required to turn in a "free floating" condition, making the maneuver much more difficult.

Summary

The shipmasters tended to rate the two plan channels higher in difficulty, attention required, and danger of grounding than the 300-ft existing channel, as would be expected with reduction of channel width. The differences in the ratings for each channel were small, and neither of the two proposed 225-ft channel plans stood out as being clearly superior to the other. The shipmasters verbally expressed that they preferred to have the navigation channel centered between the jetties, as in Plan B, but expressed no opinions about either of the 225-ft channel proposals upstream of the jetties.

Final Questionnaires

After finishing all test runs, the shipmasters completed a final questionnaire to give their opinions on the project as well as the simulation. Some of the comments made by the shipmasters on the project follow:

1. What is your opinion of the two 225-ft channel proposals? Which of the channel proposals (including the 300-ft original channel) do you prefer? How will the proposed channels affect safety of operation?

"The modified 225 foot channel (Plan B) is my preference. If it is to be deeper than the 300 foot channel, the 225 foot offset channel (Plan A) would be very dangerous to navigation in any adverse weather until you were well into the river, that is the section in the outer piers. As far as safety of operation in fair weather, I see no problem in the modified 225 foot channel (Plan B)."

"I like modified (Plan B) the best with the channel entrance in the center of the piers and the proposal 1 (Plan A) from the 1st bend. I would certainly like to see it left at 300 ft and three markers on the green side at the 1st sharp bend entering. I hope the sharp curve will remain at 300 ft."

"I don't think it (the two 225 ft channel proposals) will increase safety anymore. One just has to show a lot of patience entering the place and departing it. It is a slow and tedious operation at any time; taking it easy in and out at all times."

2. What is your opinion of the proposed turning basin and is it necessary?

"It is necessary if there is too much wind to enter the Harbour stern first, because I know I would not want to back out of the channel deep loaded. One can come in head 1st when wind is too strong to back in, turn in the basin and then move to load at the dock."

"I agree there should be a turning basin. And where it is proposed, it should help us to turn and be headed out in adverse weather and the size you propose should be sufficient."

3. Do you have suggestions to improve navigation of the proposed channels (alignment, channel width, navigation aids, etc.)?

"The range markers (added for Plan A) helped very much going in and out and would be very helpful even in the modified proposal (Plan B)."

4. Do you have any suggestions for improving the simulation?

"I found it hard to know when the rudder was mid-ship when you did not have a lot of time to look at the wheel. It would help to have a distinct sound as the wheel was turned past mid-ship."

"If one could have something to indicate wind direction other than digital readout. There are too many calculations to make. If it could be added on one of the screens somehow it would be an assist. Thank you for adding the stern flag staff."

5. On a scale of 0 to 10 (10 being excellent), what is your overall opinion of the simulator and of the Grand Haven simulation?

"10"

" '8' I found the simulator very good and found at times you could have been on a real ship. I found the Grand Haven simulation to be very good and I have been in this port a lot of times and did not really feel out of place on your simulation."

6. Comments?

"I have enjoyed my four days at WES and hope I have helped with the tests. I have probably learned some things about Grand Haven Harbour from these tests."

"It has been a great week (4 days). For me, it was like handling a real vessel. On a vessel, I would have a mate calling distances off forward and a wheel man at the wheel and a 30 ft wide plus wheel house to run across for judging distances off any object aft, but I rate it a 10. The adjustable table screen [a video monitor that was used to provide alternate views from the main projected image] serves much the same purpose as my last statement. Maybe a 1000 horsepower bow thruster. The 850 (hp) was quite effective though when one got used to it." (This shipmaster commented during testing that he rarely called for more than three-quarters thrust from his bow thruster since any extended use of the electrically powered thruster at full power caused blackouts where he lost all use of the thruster. Therefore, in reality, he hardly ever had the full 1,000 hp available. The simulator allowed use at full thrust without any danger of blackout, probably providing as much thrust as the shipmaster normally used.)

Average Clearance Distance

During each test run, the minimum clearance distance from the vessel to the defined channel edge was recorded each 5 sec. This clearance distance was the closest distance from either end of the ship to the channel edge. All of the individual shipmaster runs for the same test condition were combined and averaged to provide the average clearance for each test condition. Clearance distances (starboard and port) were plotted against the distance along track. Distance along track was the distance along a line from the origin point (for inbound runs) in Lake Michigan through the center of the channel up to the railway swing span bridge. All runs, whether inbound or outbound, were plotted versus this distance, with the outbound runs being plotted from right to left as they descended down the channel. Reference for the distance along track is provided in Plate 14.

Inbound, forward

For the existing condition runs (Plate 15), the shipmasters averaged staying within the channel for the entire run. At approximately 9,000 ft along track, they averaged being almost on top of the left descending channel edge and at 11,000 ft they averaged being on top of the right descending channel edge. However, for the majority of the transit, they had little difficulty. For Plan A (Plate 16), they again averaged almost no clearance on their starboard side at 9,000 ft along track. They averaged being slightly outside the right descending channel edge starting at about 13,000 ft along track and peaking at approximately 14,000 ft. The maximum negative clearance was 25 ft. Except for this, the runs appear to have been made with little difficulty. For Plan B (Plate 17), the runs average to be almost in the center of the channel for almost the entire run. There was no clearance distance less than 25 ft until they reached the end of the run near Verplank, where the values to port went to negative values. This is probably due to the shipmasters coming up to and alongside the Verplank Dock, which falls outside the defined navigation channel. Plan B appears to be somewhat better for this transit condition than either the existing channel or Plan A.

Inbound, backing

The existing channel runs (Plate 18) show that the shipmasters tended to be set down into the left descending bank (their port side when backing into the channel) at the first bend at 5,000 ft along track. The average clearance at this point was only 10 ft. At approximately 9,000 ft along track, the clearances on both sides averaged near zero or less. This is due to the orientation of the vessel within the channel, having the stern near or outside the channel edge on one side and the bow near or outside the edge on the other side. The track plots of both shipmasters show that much maneuvering was required in this turn at that point. After this point, the remainder of the run was made with little difficulty. For Plan A (Plate 19), the transit up to the Corps boat yard was made with little difficulty. Starting at the boat yard, the average port side clearance went to negative values, peaking at -80 ft at approximately 9,000 ft along track. Most of the remaining transit was made with negative clearance to port. Near the end of the run, both clearances were negative. This indicates that this channel is considerably more difficult to navigate for this condition than the existing channel. For Plan B (Plate 20), the average clearances show no difficulties at all for almost the entire run. For the most part, the clearances show the shipmasters stayed near center channel for almost the entire transit. The only negative clearances were near the end of the transit as they approached the Construction Aggregates Dock. As in Plan A, the shipmasters required considerable maneuvering as they approached the Construction Aggregates Dock, going out of the defined channel on both sides. The maximum value of negative clearance both port and starboard was 30 ft. For this run condition, the ship was in ballast at 18.5 ft and the defined navigation channel was 27 ft; therefore, the vessel actually had more maneuvering room than just inside the defined channel. The Plan B clearance plots indicate that this run condition was much easier than in Plan A and somewhat better than with the existing condition.

Outbound, forward

The existing channel condition (Plate 21) shows that there was little difficulty in making the transit. The large negative clearance at 13,000 ft along track should be discounted since the run started with the vessel alongside the Construction Aggregates Dock and sitting outside the defined channel line. This will be true for all the test channels with outbound, forward runs. For Plan A (Plate 22), the port side clearance was much less than during the existing condition for almost the entire run, but there were no negative clearances during the transit. At approximately 8,500 ft along track, the closest clearance was 15 ft. For Plan B (Plate 23), the shipmasters again tended to average being near the channel center line with no clearance difficulties anywhere along the track. The minimum clearance was 25 ft as the vessel cleared the end of the jetties. Plan B appears to be considerably better than Plan A and only slightly more difficult than the existing channel for this condition.

Outbound, backing

The existing channel (Plate 24) shows that almost all of the transit was made with little difficulty. There was a slight port negative clearance (10 ft) at the ends of the jetties and about a 30-ft negative starboard clearance near the Verplank Dock. For Plan A (Plate 25), the passage was made with considerably more difficulty. The starboard clearance stayed very close to or less than zero from the start of the transit to the Corps boat yard. The large negative value at 9,500 ft along track (-45 ft) is due mostly to Pilot G, who stayed well outside the left descending channel line through the bend above the boat yard. Pilot H made a much better transit, but the average of the two yielded a cumulative negative clearance in this bend. Both shipmasters had similar problems in the bend between Verplank and Construction Aggregates. The clearances improved from the boat yard to the bend at 5,000 ft along track. As in the bend above the boat yard, Pilot G went well outside the left descending channel edge, and although Pilot H made a good passage, the average still showed negative starboard clearance. At the ends of the jetties, both shipmasters were near or outside the right descending channel edge. For Plan B (Plate 26), the clearances from Verplank down to the bend at 5,000 ft along track were much better than with Plan A. Port side clearances tended to be low, but except for one small negative clearance at 8,500 ft (-5 ft), they remained positive until the bend at 5,000 ft along track. At this bend, Pilot G tended to stay very near the left descending channel edge and Pilot H near the right descending edge. These averaged out to give negative values for both sides, although Pilot H stayed within the defined channel from the bend through the jetties. Pilot G stated that he had misinterpreted the wind effect on the vessel and compensated incorrectly, causing the poor starboard clearance for the transit between the bend at 5,000 ft along track and the end of the jetties. Taking this into account, it appears that Plan B is slightly less difficult than Plan A and slightly more difficult than the existing condition.

Summary

For all the conditions tested, the average clearances indicate that Plan B would be better than Plan A. Plan B appears to be equal to or slightly better than the existing channel for inbound runs, either forward or backing, and slightly worse for the outbound conditions.

Elapsed Time of Runs

Every 5 sec during testing, the elapsed time from the start of the run was recorded along with the position of the center of gravity of the vessel. This information was used to compare similar runs with the different channels to give an indication of increased difficulty in operation due to longer elapsed time to cover the same distance. Elapsed time was used instead of average speed, since shipmasters constantly changed engine commands and many times actually changed direction of motion briefly as they corrected the position of the vessel, making analysis of average speed difficult if not impossible. The test conditions for each shipmaster and their elapsed times between starting and ending points are summarized in the following tabulation.

For inbound, backing runs, both shipmasters required less time for Plan A than either the existing or Plan B channels. Inbound backing required almost the same time for Pilot G for the existing and Plan A channels and 10 min less for Plan B, while Pilot H took 11 min less for Plan A than for the existing channel and almost 5 min longer than the existing for Plan B. For the outbound, forward runs, Pilot G took a little longer for Plan A than for the existing channel and 2 min longer for Plan B than Plan A. Pilot H took longer for Plan A than for the existing channel and less time for Plan B than for either

Passage	Elapsed Time for Passage, min					
	Pilot G			Pilot H		
	Existing	Plan A	Plan B	Existing	Plan A	Plan B
Inbound, forward	48:05	43:20	49:25	89:25	61:30	82:25
Inbound, backing	55:30	54:15	44:30	48:50	37:00	53:10
Outbound, forward	30:40	34:50	36:55	36:35	39:10	33:55
Outbound, backing	39:10	56:50	83:40	40:55	60:10	49:00

the existing channel or Plan A. For the outbound, backing runs, Pilot G took over 17 min longer for Plan A than for the existing channel and over twice as long for Plan B as for the existing channel. Pilot H took almost 20 min longer for Plan A than for the existing channel but only about 8 min longer than for the existing channel for Plan B.

No clear pattern developed from comparing the elapsed times of the runs. For the most part, times taken to complete the runs were not extremely different from one plan to another, except for Pilot G's outbound, backing run with Plan B, which required over twice as much time as the existing channel, but for which Pilot H's same run was only a few minutes longer. Greater familiarity with the two plan channels would probably improve passage times.

Individual Ship Track Plots

A complete set of the individual ship track plots for the channel test conditions is presented in Plates 27-54.

Inbound, forward

Existing channel. Pilot G (Plate 27) tended to stay near the left descending bank until he passed the confluence. It appears he started the turn at the Corps boat yard late, backed off the turn early, or had too much speed, causing the ship to go very near the channel edge opposite the second green buoy. As he tried to bring the ship back to midchannel, he was late reversing his turn from port to starboard. To prevent running out of the channel to his port side, he put the engine full astern and brought the ship to almost a complete stop. This can be determined by the heavy concentration of ship plots just upstream of the confluence. Ship plots are more widely spaced when a ship is moving fast and more closely plotted when a ship is going slow. After bringing the ship under control, he completed the run up to Verplank with little difficulty. There were two places that the ship strayed beyond the channel limit, but these were only by a few feet and were out of the channel only briefly. Pilot H (Plate 28) had an extremely good run with almost no difficulty. He tended to stay near the right descending bank at the turn at the Corps boat yard. His passage was considerably slower than Pilot G's. This can be seen by the heavier concentration of ship plots throughout the channel compared with Pilot G's run, especially between the jetties and the confluence. It appears that too much speed leads to control problems, especially in the turns.

Plan A channel. Pilot G (Plate 29) made a good passage throughout the channel. The stern got near the channel edge just upstream of the Corps boat yard, and he let the ship get close near the confluence of the two channels; but it appears there was little difficulty in the passage. Pilot H (Plate 30) tended to have a little more difficulty. He ran very near the left descending channel edge at the first turn, then was in danger of grounding in the turn upstream of the Corps boat yard. To avoid grounding, the shipmaster put the engine astern and came almost to a halt, then used the bow thruster to turn the vessel before continuing forward. He performed this same maneuver just upstream of Construction Aggregates Dock, but here he let the stern back out of the channel slightly.

Plan B channel. Pilot G (Plate 31) made a very good run till he passed Construction Aggregates. As he approached the gated buoys, he let the ship get into and outside of the right descending channel edge. It is unclear why he went outside the channel here since the vessel was in excellent position as he passed Construction Aggregates. Pilot H (Plate 32) again tended to have a little more difficulty than Pilot G. He got very near the right descending channel edge just downstream of the Corps boat yard, then stayed very near the right descending edge until he completed the turn near the confluence. He stayed very near the left descending channel edge in the turn from Construction Aggregates up to Verplank. Staying near the inside of the turns was probably a matter of choice rather than an indication of control problems.

Inbound, backing

Existing channel. Pilot G (Plate 33) tended to have some control difficulties in the bends. At the first bend, he neared the left descending channel edge. To push the stern out from the bank, he put the rudder hard over and brought the engine ahead. This stopped the movement of the vessel and actually caused it to go forward slightly. As he started the turn at the Corps boat yard, he almost went out of the channel, put the engine ahead and the rudder over, and pushed the stern out, actually coming ahead too hard or long and causing the stern to go out of the channel on the opposite side. After this, he completed the rest of the transit with little difficulty. Pilot H (Plate 34) made the transit somewhat easier than Pilot G. He too put the engine ahead and rudder hard over to move the stern of the ship away from the bank, but did not require as much correction as did Pilot G. He went slightly out of the right descending channel edge between the Corps boat yard and the confluence. Most of the passage appears to have been made with little difficulty.

Plan A channel. Pilot G (Plate 35) had little difficulty until the turn just upstream of the Corps boat yard. He let the bow swing around too far, going out of the defined channel on the left descending side. As he went further upstream, he got too close to the left descending side and again let the bow swing too far out. He then turned too hard toward the right descending bank, causing him to put the engine ahead and push out the stern. He virtually stopped the linear motion of the ship until he obtained the desired position within the channel, then continued on upstream to Construction Aggregates. Pilot H (Plate 36) again had a much smoother run than Pilot G. He let the bow swing very near the left descending bank just upstream of the Corps boat yard, just barely going outside the defined channel. He passed by the confluence with no difficulty. As he approached the bend just downstream of Construction Aggregates, he had the stern too close to the right descending bank. He put the engine ahead with hard starboard rudder to push the stern over, but overcorrected and went slightly out of the left descending channel edge.

Plan B channel. Pilot G (Plate 37) had a good passage until he reached the start of the bend just downstream of Construction Aggregates. As he approached the bend, his stern was close to the right descending bank. He put the engine ahead with hard starboard rudder to push off the bank. He again went ahead too long and hard, actually going back downstream and causing the ship to go out slightly on the left descending bank side. He then let the bow swing out toward the right descending bank too far, causing it to go slightly outside of the defined channel. He completed the run very near the left descending channel edge across from Construction Aggregates. Pilot H (Plate 38) made a good passage up to the bend upstream of the Corps boat yard. As he started the turn, he brought the engine ahead and rudder hard to port, causing the ship to come very near the right descending channel edge. He again did this maneuver at the confluence and again put the ship near or slightly outside the right descending channel edge. As he started the turn at Construction Aggregates, the stern was near the right descending channel edge. He put the engine ahead with hard starboard rudder and the vessel actually went back downstream with the stern near to or past the left descending channel edge. He completed the run with the vessel very near the left descending channel edge.

Outbound, forward

Existing channel. Pilot G (Plate 39) made a smooth run with no difficulties. At the start of this simulation scenario, the ship was sitting alongside the Construction Aggregates Dock; therefore, the plots of the vessel outside the defined channel at the dock are due to the startup condition and not the shipmaster. He passed near the center of the channel throughout, except downstream of the Corps boat yard, where the vessel neared the left descending channel edge. Pilot H (Plate 40) also made a good run. He tended to stay nearer the inside of the bend between the confluence and the Corps boat yard and made the turn slower than Pilot G. Again, an indicator of speed is the concentration of vessel plots. Pilot H's plots through the bend are more concentrated and the spacing between each individual vessel plot smaller than that of Pilot G for the same area, indicating that Pilot H's speed through the turn was less than that of Pilot G. Pilot H also appeared to have no difficulties with the run.

Plan A channel. Pilot G (Plate 41) made the run successfully, but tended to run the channel edges instead of the center, probably a reflection of the narrower channel. Just downstream of the Construction Aggregates Dock, he stayed very near the right descending channel edge. Just upstream of the confluence, he crossed from the right to the left bank, then hugged the left descending bank through the bend until well past the Corps boat yard. After that point, he maintained the vessel closer to the channel center and completed the run. Although the tracks were very near the channel edges, it appears that the vessel never went out of the defined channel. Pilot H (Plate 42) made a very smooth run. He stayed near the channel center until he got to the jetties. He also made the turn between the confluence and the Corps boat yard slower than Pilot G, possibly accounting for his excellent position within the channel. He appeared to turn a little slow in the last bend upstream of the jetties and allowed the vessel to near the left descending channel edge, overcompensated, and then finished the run near the right channel edge.

Plan B channel. Pilot G (Plate 43) made an excellent run. He stayed near the channel center throughout the run and appeared to have no difficulties at any time. Pilot H (Plate 44) made a successful run, but tended to stay near the right descending channel edge for most of the passage. This appears to be the shipmaster's choice rather than an indication of control problems. Although he stayed near the channel edge, it appears that he did not go outside the defined channel at any time during the transit. Pilot H tended to favor the right side of the channel for most of his runs, both during validation and testing. He was not questioned directly about this, but this would appear to be his tendency in real-life operation in this channel.

Outbound, backing

Existing channel. Pilot G (Plate 45) made a good passage until he neared the jetties. He stayed close to the center of the channel until he passed the Corps boat yard, then stayed near the left descending channel edge. As he passed through the last turn upstream of the jetties, the vessel set into the channel edge and eventually went outside the channel. This was probably due to the shipmaster's interpretation of the wind direction from the precision navigation screen. Wind direction on the precision navigation screen is given by a numerical value for angle and speed. The angle is referenced relative to the ship heading. This means that a wind coming directly into the bow would have an angle of 0 deg; directly into starboard, 90 deg; directly into the stern, 180 deg; directly into port, 270 deg. As the shipmaster passed through the jetties, his compass heading should have been 82 deg (since he was backing, the actual direction of travel was 262 deg). For the simulation, the wind was set to come from the northwest toward a compass heading centered on 135 deg (direction in which the wind is blowing) and randomly varying up to ±15 deg from the specified angle. Wind direction relative to the ship heading was indicated as approximately 220 deg, actually setting the ship to starboard. The shipmaster was interpreting the wind direction to be coming from a compass direction of 220 deg, which should have set his vessel to port. He was compensating for the expected set to port by being near the starboard edge of the channel. This led to his vessel going outside the defined channel. The shipmaster stated that he normally looked at the flags on his vessel to judge how the wind was affecting the vessel. Due to this problem, the precision navigation screen was changed to show a directional vector, similar to a flag, to help the shipmasters quickly see how the wind was blowing in relation to their vessel. These changes were made before Pilot H tested, but were not available while Pilot G was testing. Time did not allow a repeat of this run, but with the exception of the passage through the jetties, the run was made with little difficulty. Pilot H (Plate 46) made a fairly good passage. He got very near the right descending channel edge just downstream of the confluence, put the engine ahead to push the stern to port, brought the stern very near the right descending channel edge opposite of the Corps boat yard, and turned too fast at the last turn upstream of the jetties, putting the stern almost on the channel edge. It appears that the vessel might have gone slightly outside the defined channel edge in one or two places, but only by a few feet and very briefly.

Plan A channel. Pilot G (Plate 47) appears to have had difficulty in controlling the vessel through the passage. As the ship pulled away from the Verplank dock, it drifted down onto the left descending channel edge. This was likely due to the northwest wind and lack of steerage while the vessel was moving very slowly. The same conditions occurred during the existing condition runs, but with the 300-ft width channel, there was more room for correction. He applied forward engine and hard starboard rudder, pushing the vessel forward and out of the right descending edge. As he brought the ship astern again, the vessel drifted down into the left descending channel edge and remained there until passing the Construction Aggregates Dock. He maintained the vessel within the center of the channel from Construction Aggregates down to the confluence, then pushed the bow out toward the left descending bank to make the turn down to the Corps boat yard, going slightly out of the channel. As he passed the boat yard, the bow tended to ride along and slightly outside the left channel edge. He pulled out to center channel briefly just upstream of the last bend, then let the bow go out along the left edge until just before clearing the ends of the jetties. The strong wind from the northwest probably influenced how he made the transit and again possibly caused some confusion on how the wind was blowing relative to the ship, as explained earlier. Pilot H (Plate 48) also had difficulty in getting away from the Verplank dock without drifting out on the left channel edge. As he neared the channel edge, he came ahead with the engine and hard to starboard, then brought the engine astern once he had come out near the channel center. He repeated this several times between Verplank and Construction Aggregates, staying on or slightly outside the left channel edge. As he completed the turn downstream of Construction Aggregates, he brought the ship to center channel and completed his transit with little difficulty. He came very near the right channel edge between the confluence and the Corps boat yard and from the last bend to the end of the jetties, but again Pilot H tended to favor the right descending channel edge for most of his transits.

Plan B channel. Pilot G (Plate 49) again had difficulty in staying inside the left channel boundary as he came off the dock. He applied forward engine and hard starboard rudder at least twice and went out on both the left and right sides of the channel. As he passed by Construction Aggregates, he again corrected his position with forward engine and hard starboard rudder, but this time he remained within the channel boundaries. From here, he passed below the Corps boat yard with little difficulty, but used almost all of the channel available in the bend between the boat yard and the confluence. Below the boat yard, the vessel set down on and remained on or outside the left descending channel boundary. The shipmaster did not sense bank forces as he passed the navigation channel boundary because this boundary marked the 27-ft-depth channel and since the vessel was drafting only 18.5 ft, there was no bank for it to "feel" until the vessel reached the existing bank line near the jetties. Again, the shipmaster may have misinterpreted the wind direction and compensated incorrectly for the wind force on the vessel. Pilot H (Plate 50) had much less difficulty in getting away from Verplank. He did pass along the left channel edge, but due to the defined edge marking a 27-ft-depth channel, was in no danger of grounding. As he passed downstream of Construction Aggregates, he came to midchannel down to the next bend, then again stayed near the right descending channel edge through the bend. Below this bend, he maintained the vessel near midchannel and passed on through the jetties with no apparent difficulty.

Turning basin runs

Inbound, forward. For these runs the shipmaster was allowed to start his passage upstream from the confluence, come upstream, turn within the proposed basin, and come back downstream to Construction Aggregates. The simulation does not provide a "solid" bank; therefore, it would not allow the shipmaster the option of resting the bow in "the mud" and pivoting around the bow. This would be the common practice for a vessel this size making a turning maneuver without tugs in a turning basin such as this. The shipmaster had to turn the vessel using the engine, rudder, and bow thruster. The current and wind caused a lateral drift that would in normal practice be controlled by "pivoting" around a stationary bow. Although the simulation will not allow completely realistic conditions for turning, it should be sufficient to determine adequacy of size and location and also give the shipmasters an impression of its necessity. Also, it should be remembered that turning was with a ballasted ship, so adequate depth was available well outside the defined 27-ft channel outline. In addition, it should be remembered that the shipmasters had never performed such maneuvers, so this was a first-time maneuver.

Pilot G (Plate 51) was being set toward the left descending bank as he slowed to pass Construction Aggregates and enter the turning basin. As he entered the basin, he brought the ship to an almost dead stop and applied full bow thruster to push the bow to starboard. As the bow started turning, he brought the engine ahead slow to help hold against the current and wind and to pull the stern upstream. With no solid bank, the bow passed outside the defined turning basin boundary as the stern was pushed upstream. The stern went slightly out on the right descending side during the turn, but this was due to the shipmaster attempting to keep the bow from going out of the defined channel and from overbacking to clear the bow from striking the buoy marking the southwest corner of the channel. The vessel was turned too far at the completion of the basin maneuver, and the run ended with the bow of the vessel outside the right channel edge. Most of the northeast corner of the basin was not used, possibly due to the current and wind set to the south. Pilot H (Plate 52) was able to complete the turn in the basin by turning the bow to starboard with the thruster and driving forward; however, he ended up going well outside the basin limits. He then came astern and came back into the basin, still using full bow thruster to starboard. He completed his run within the defined channel. The stern went out of the right descending channel edge slightly as he began his turn; however, this area would be dredged for the dock area. Pilot H used most of the available basin area, except for the portion in the extreme southeast corner.

Outbound, backing. For this run, the shipmasters were asked to start from the docked position at Verplank, back down into the basin, turn, and go downstream bow first from the turning basin. Pilot G (Plate 53) was again set into the left descending channel edge. He backed into the middle of the basin, applied full starboard bow thrust, and used the engine and rudder to push the stern upstream. He completed his turn by letting the bow swing outside the defined basin limits. As he completed the turn, he backed too far and the stern went outside the channel limits. As he started downstream out of the basin, the bow was into the right channel edge. He turned the ship hard to port, turning the ship into the left channel edge. He corrected for this, overcompensated, and was correcting for the overcompensation when the run was terminated. Pilot H (Plate 54) backed from Verplank with better control than in earlier runs. He entered the basin and used the same technique as described for Pilot G. He was better able to maintain his position within the basin while he rotated. He completed the turn well down in the basin, causing him to turn back to port to come back into the channel. His bow went slightly out of the defined channel during this turn, but he completed the run centered in the navigation channel.

5 Conclusions and Recommendations

Limitations of the Study

There are several limiting factors in determining test results and conclusions that can be reached. There was no available current or discharge information for the Grand Haven Harbor channel, so the currents generated by the TABS-2 numerical model could not be verified either by magnitude, direction, or distribution. The original magnitude used for the desktop simulation study was based on the U.S. Coast Guard WAMS report,[1] which stated that currents ran as high as 5 mph during peak runoff. This was most likely an estimated surface velocity since no known recorded velocities exist. Direction, magnitude, and distribution were strictly what was generated by the TABS model. The TABS model generates depth-averaged currents; therefore, the estimated surface current could be used only as a guide. The original TABS currents for the study had a maximum velocity of approximately 6 fps (4 mph). All the shipmasters found the current to be too strong, even after the validation shipmaster had requested that they be reduced by 30 percent to a maximum of approximately 4 fps. The validation for the full ship simulations started with the 4-fps current from the previous validation. The shipmasters were requested to base their judgement of current strength on what would be the maximum current into which they would back the test vessel into Grand Haven. Both shipmasters independently reached the same conclusion that the currents should be reduced to approximately 1.6 fps (about 1.1 mph). Since the currents could not be validated to any prototype information, they were adjusted to the shipmasters' experience, based on backing into the channel. All testing was performed using a 749-ft vessel with both forward and backing operations. Both shipmasters were very familiar with these operations in the channel with vessels of this size, using only a bow thruster.

The wind effect on the vessel was constant with gusting characteristics. There was no shielding effect by the topography as there would be in the prototype. Determining the wind direction and effect on the ship was also a

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1 Personal Communication, 28 August 1986, from Commanding Officer, USCGC *Acacia*, Subject: WAMS Study of Grand Haven, Michigan Harbor.

problem for one shipmaster. This was corrected for the second shipmaster by showing a directional vector on the precision navigation screen, but this was not developed in time to aid the first shipmaster.

Marking the Plan A channel with navigation aids may also be difficult. The Plan A 225-ft channel used the right descending channel line of the 300-ft channel, and the total reduction in width came from the left descending bank side. To help the shipmasters in navigating this "offset" channel, range markers were added on the land, upstream of the jetties. The U.S. Coast Guard had been queried about this and had said that ranges would not be an available option; however, ranges seem to be necessary for this channel plan.

As stated earlier, the information used for currents could not be verified to any prototype data and is based solely on the shipmasters' experience. By allowing each shipmaster to perform validation on the currents prior to testing, the validations could be compared with each other to determine if the currents were realistic, without having to make actual current measurements. Since both shipmasters independently reached the same conclusion on current strength, there is confidence that the currents used for testing are a valid representation of what occurs at Grand Haven. The lack of a shielding effect of the topography on the wind did not appear to present any major problem to the shipmasters on any of their tests. The shipmasters made no written or verbal comment about the wind effect, other than the need for a better indication of wind direction on the bridge instrumentation as was discussed previously. Using the range markers for the Plan A channel made passage through the jetties easier, according to the shipmasters' comments.

Conclusions

Based on the real-time shipmaster results and comments, the following preliminary conclusions were reached:

a. The 225-ft channels (Plans A and B) were somewhat more difficult to navigate than the 300-ft channel for all conditions.

b. Based on average clearance distances, Plan B appears to be better than Plan A and about the same or slightly worse than the existing condition.

c. Based on the elapsed time for transits, no clear pattern of improved or worsened passage times for either of the plan channels versus the existing channel was found.

d. Based on the individual track plots, neither of the 225-ft channel proposals (Plans A and B) offers any major advantage over the other plan, except that the channel through the center of the jetties for Plan B was strongly favored by the shipmasters.

e. The proposed turning basin is adequate and useful to vessels coming inbound and turning or backing outbound from an upstream terminal, turning, and going outbound forward; however, the turning basin does not appear to be mandatory to significantly improve operation over what is currently being done with vessels larger than 650 ft in length.

Recommendations

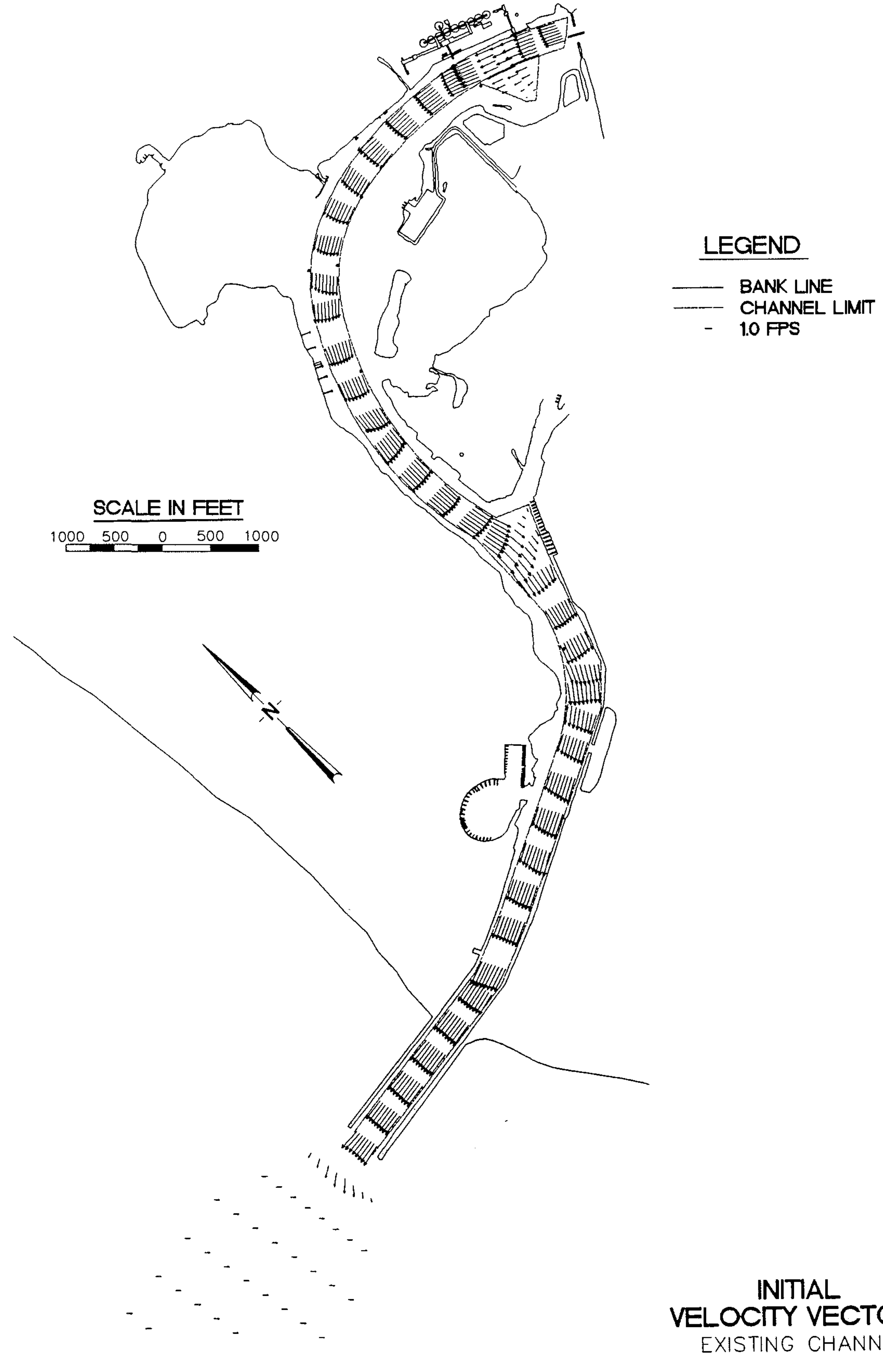
Based on shipmaster test results, comments, and conclusions reached, WES proposes the following:

a. Deepen a nominal 225-ft channel to 27 ft but maintain as much channel width as possible through the bend from the Corps boat yard to the confluence with the South Channel.

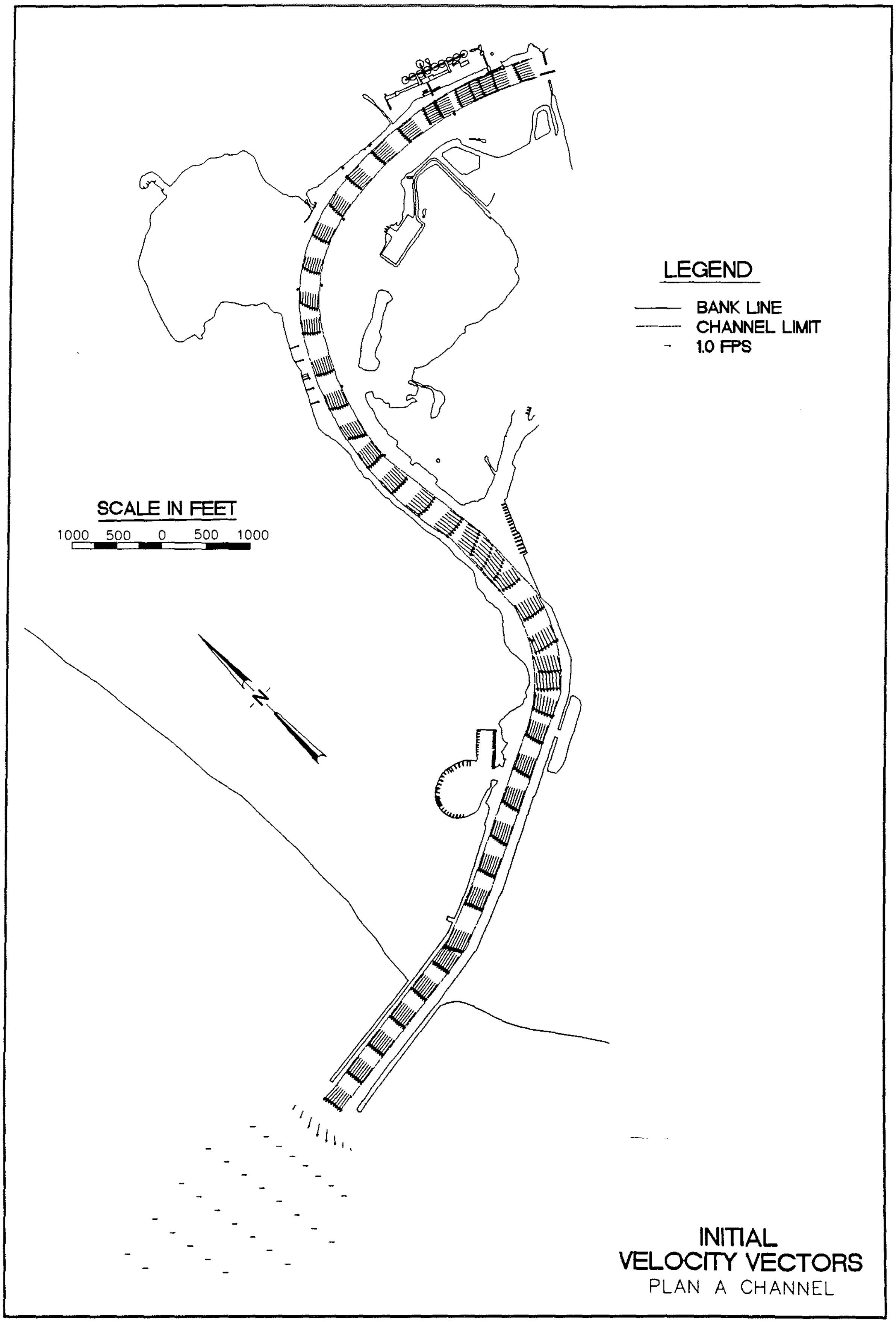
b. Center the navigation channel between the jetties, whichever reduced-width channel design is accepted.

c. Add range markers to mark the channel through the jetties.

It is further recommended that velocity measurements be taken in the harbor when river flows are near the maximum flow in which design ships will operate. These should be compared with the currents used in this model. Consideration should be given to conducting additional simulations to finalize the channel layout and dimensions.

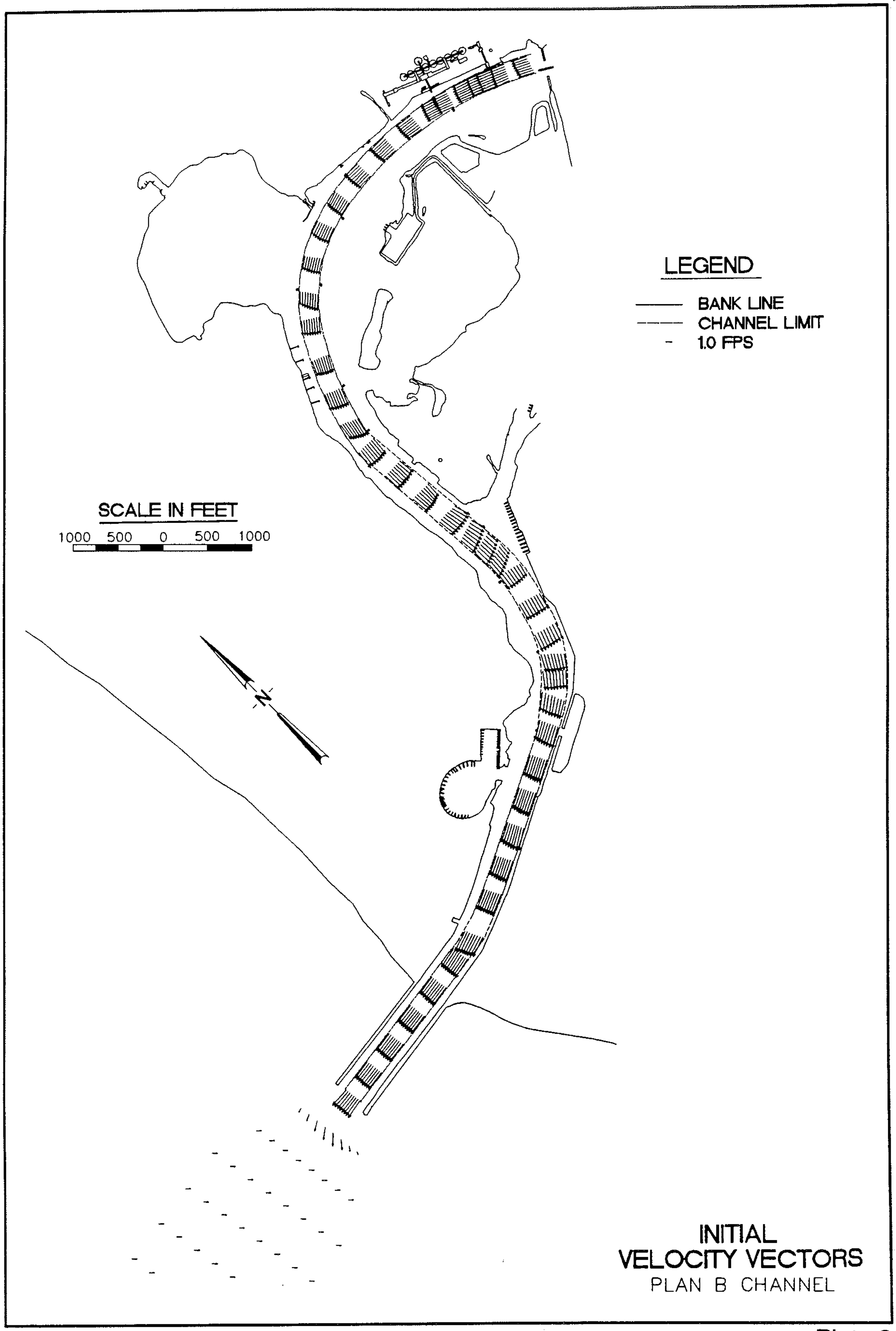


INITIAL
VELOCITY VECTORS
EXISTING CHANNEL



INITIAL
VELOCITY VECTORS
PLAN A CHANNEL

Plate 2


LEGEND
BANK LINE
CHANNEL LIMIT
1.0 FPS
SCALE IN FEET
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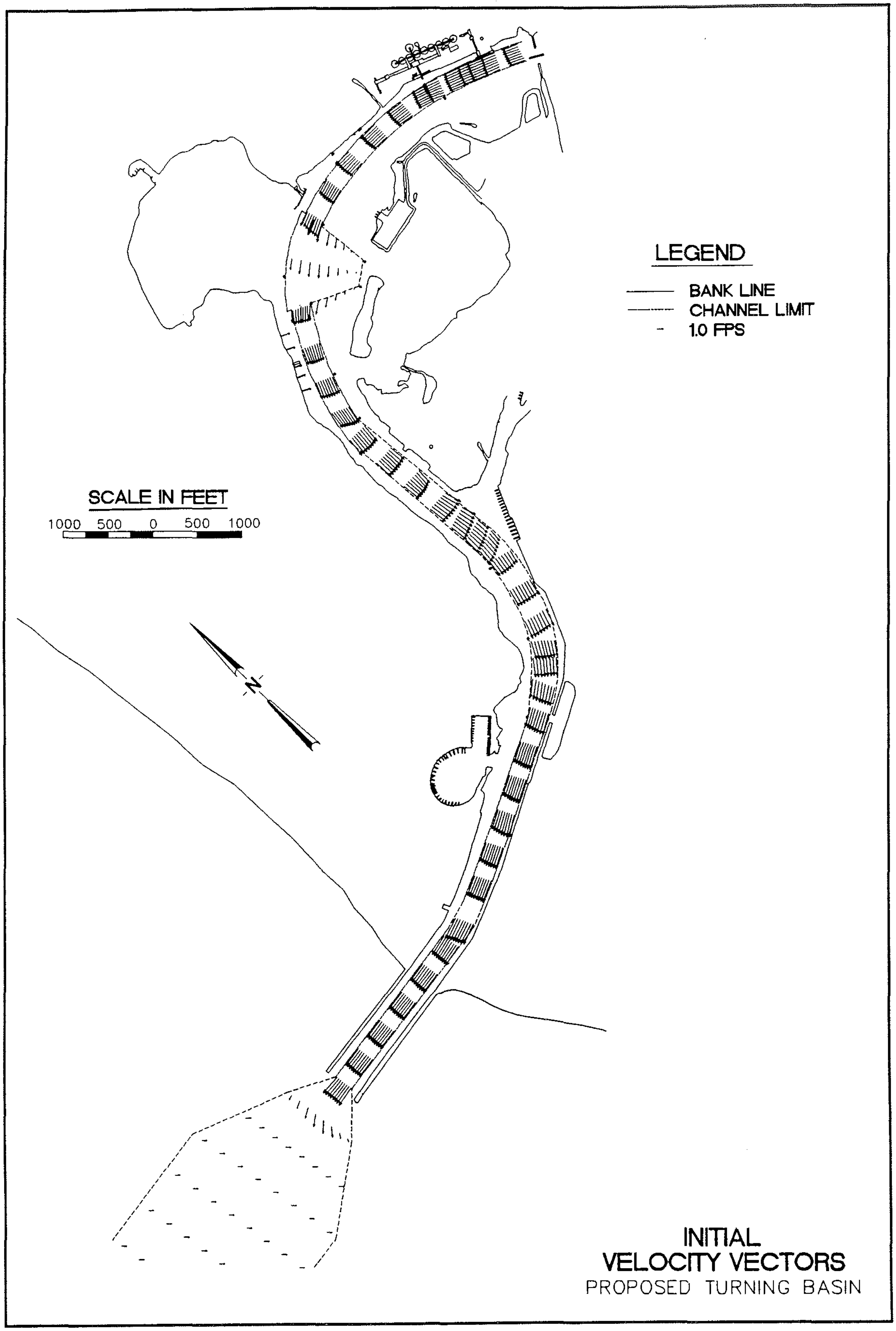
N
INITIAL
VELOCITY VECTORS
PLAN B CHANNEL


LEGEND
BANK LINE
CHANNEL LIMIT
1.0 FPS
SCALE IN FEET
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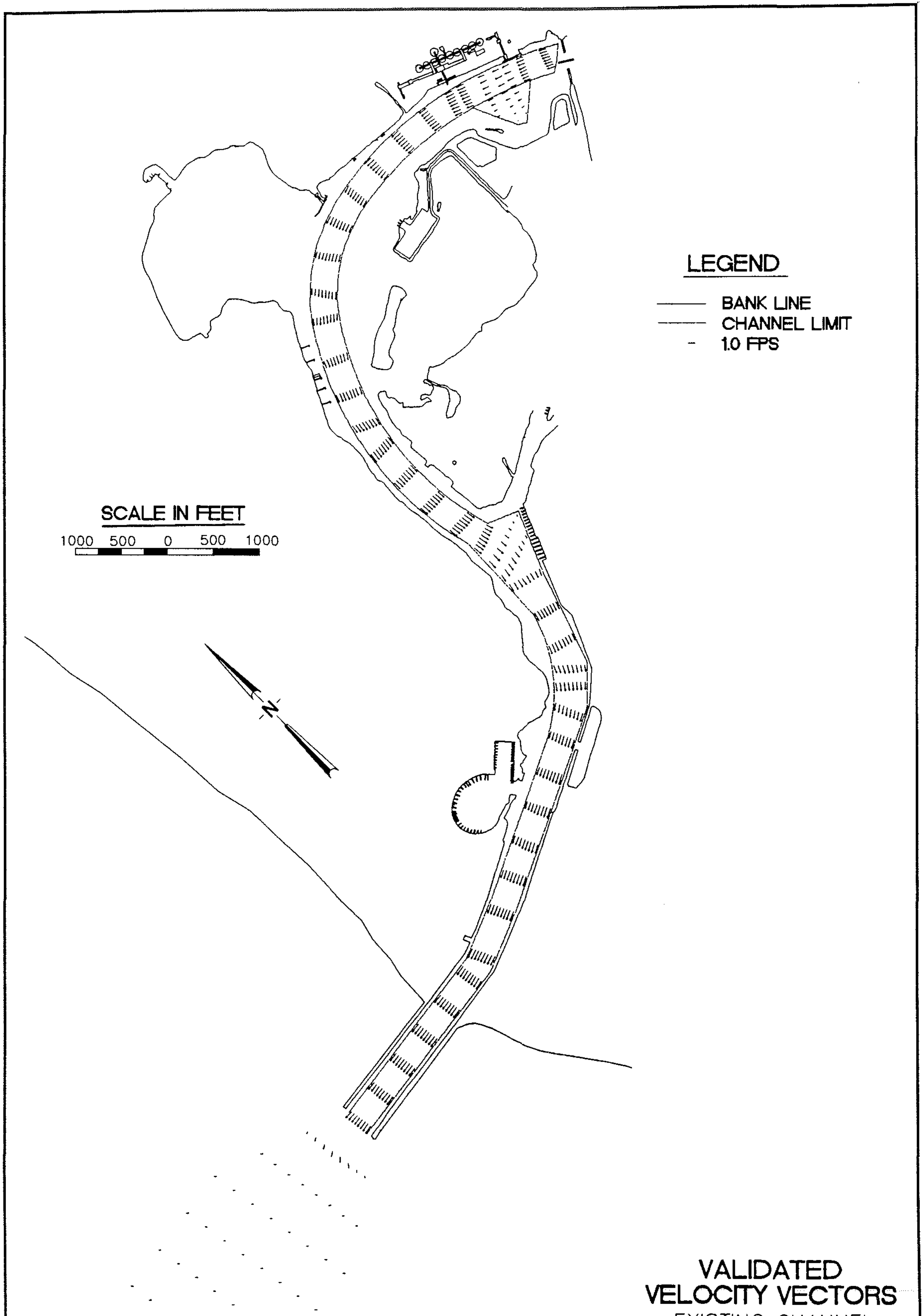
N
INITIAL
VELOCITY VECTORS
PROPOSED TURNING BASIN

Plate 4



VALIDATED
VELOCITY VECTORS
EXISTING CHANNEL

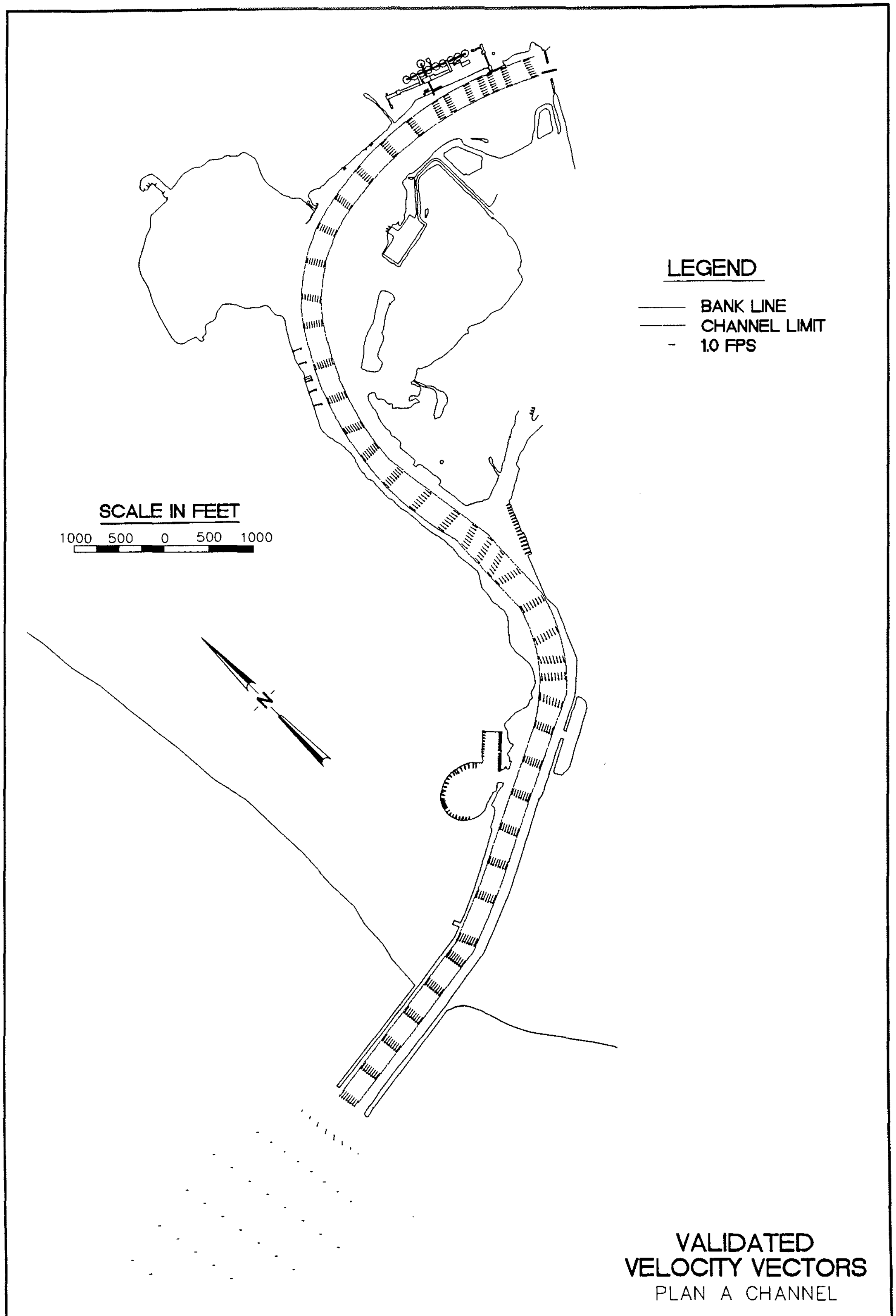
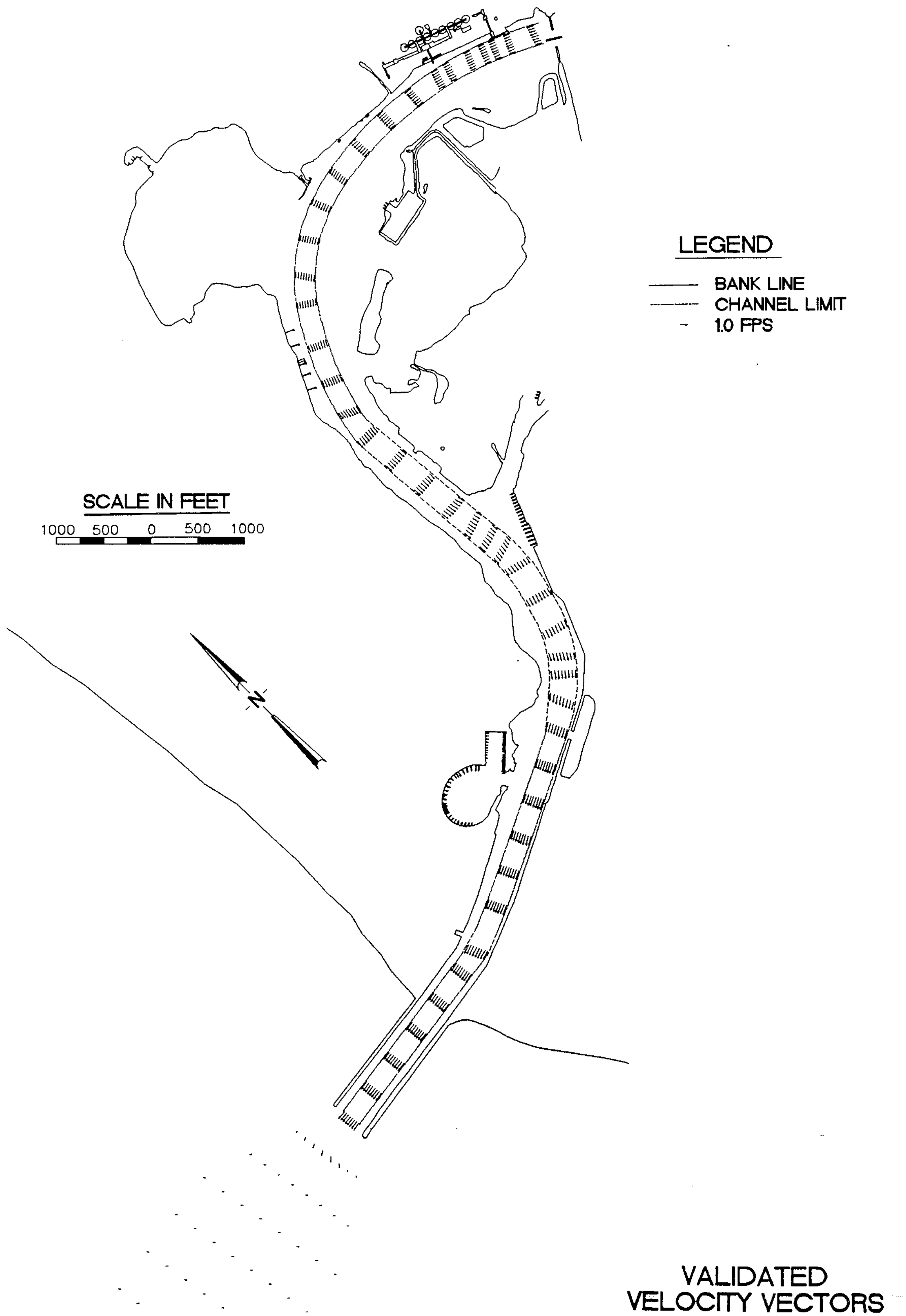

LEGEND
BANK LINE
CHANNEL LIMIT
1.0 FPS
SCALE IN FEET
1000 500 0 500 1000
N
VALIDATED
VELOCITY VECTORS
PLAN A CHANNEL

Plate 6



VALIDATED
VELOCITY VECTORS
PLAN B CHANNEL

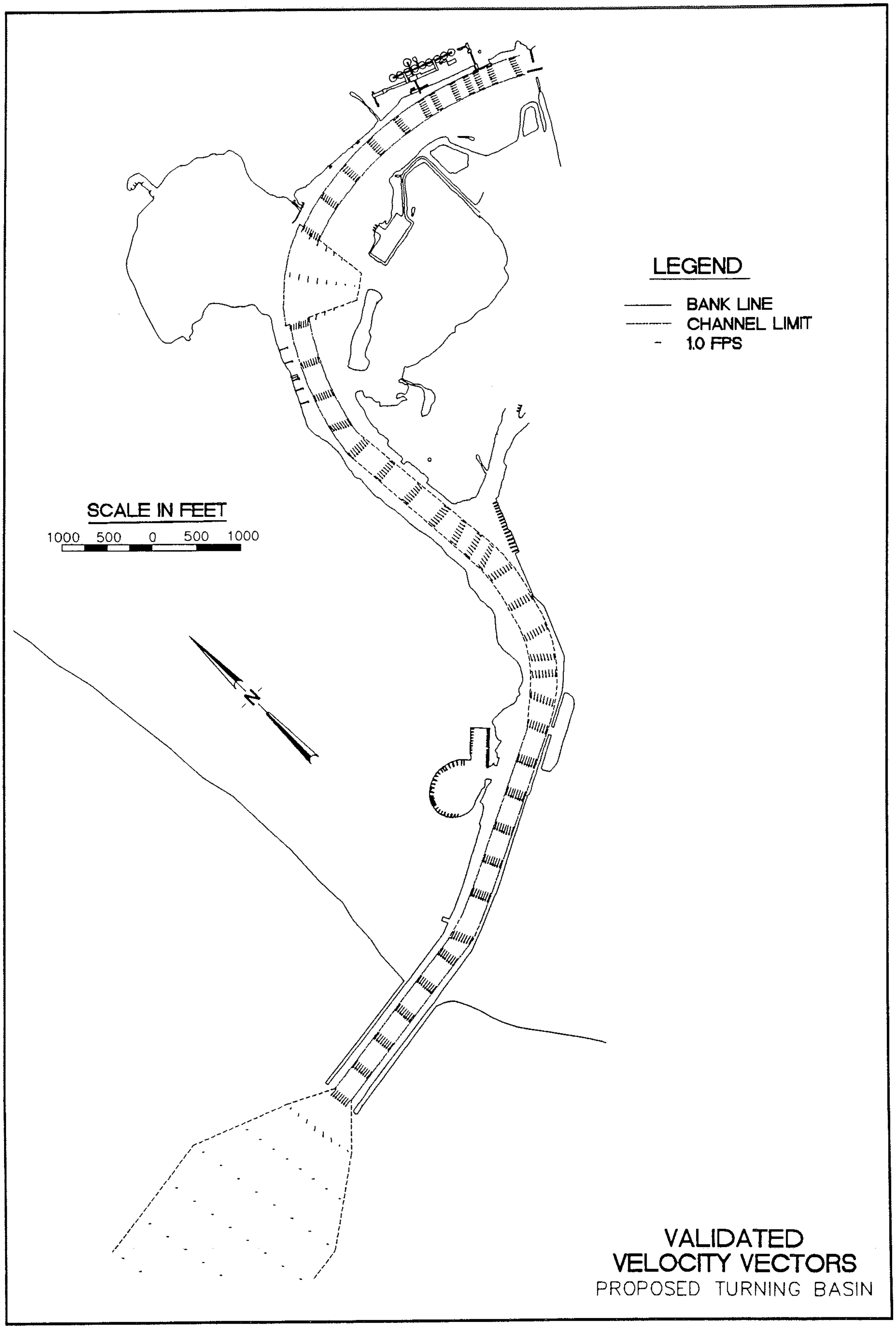
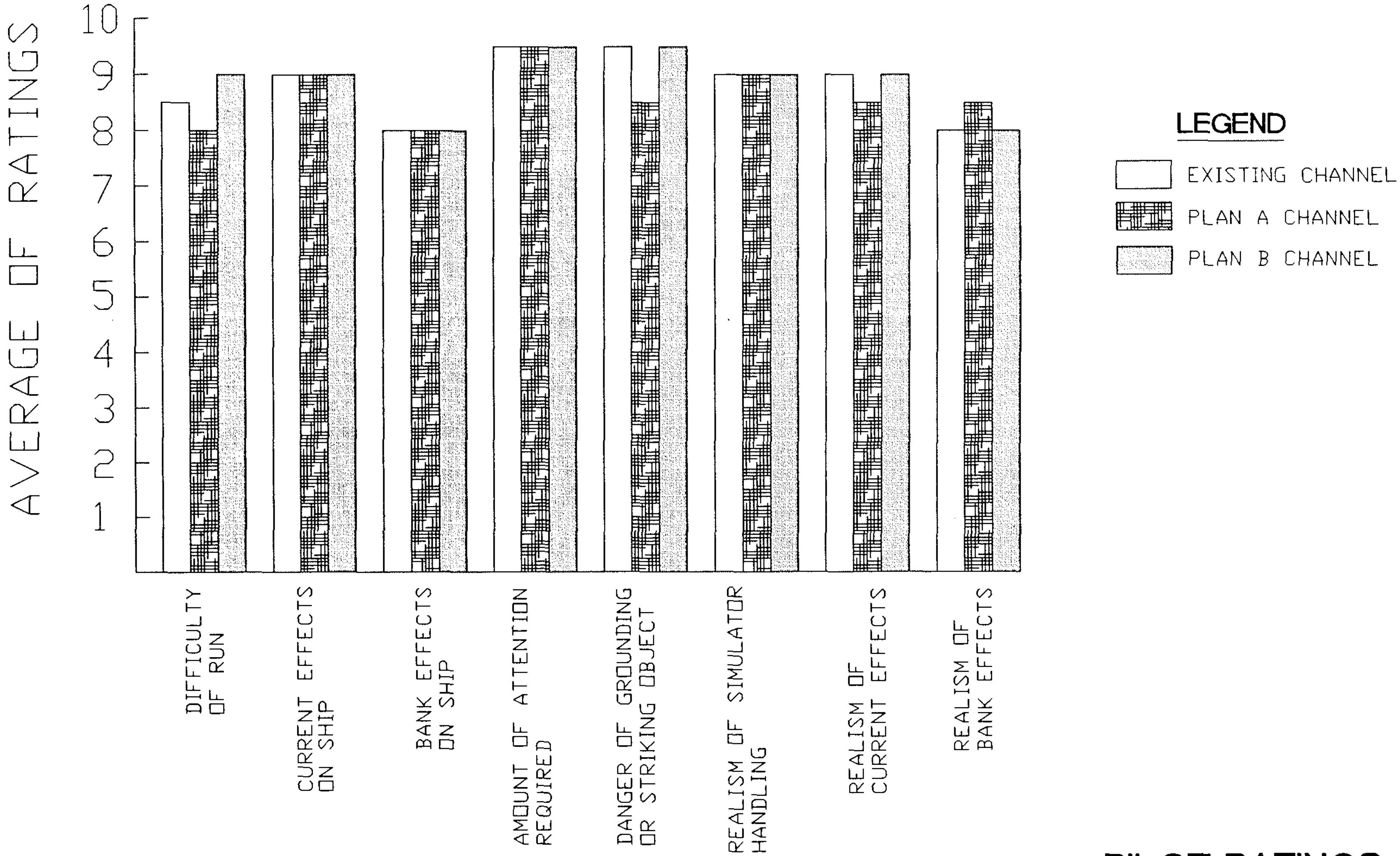

LEGEND
BANK LINE
CHANNEL LIMIT
1.0 FPS
SCALE IN FEET
1000 500 0 500 1000
N
VALIDATED
VELOCITY VECTORS
PROPOSED TURNING BASIN

Plate 8

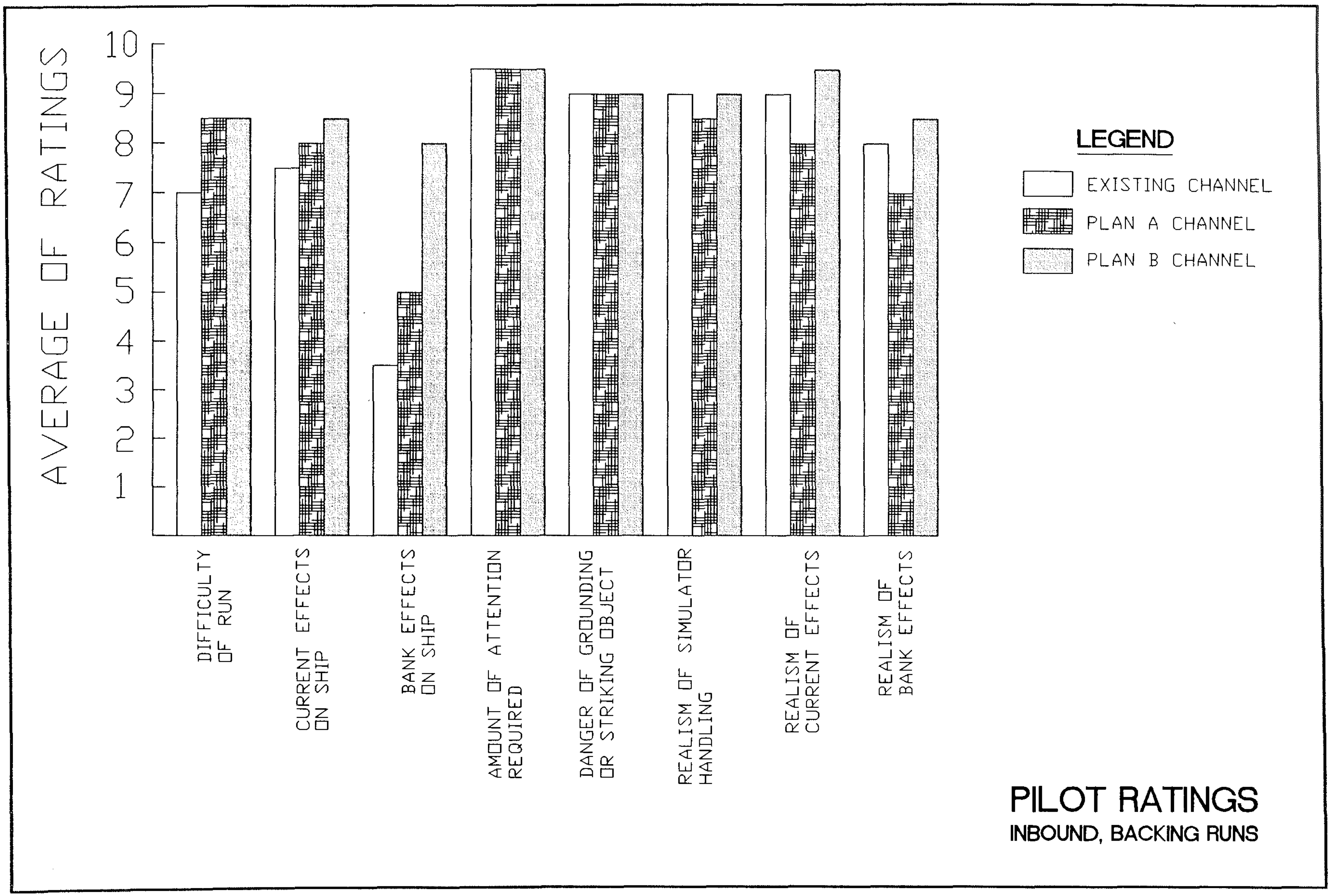


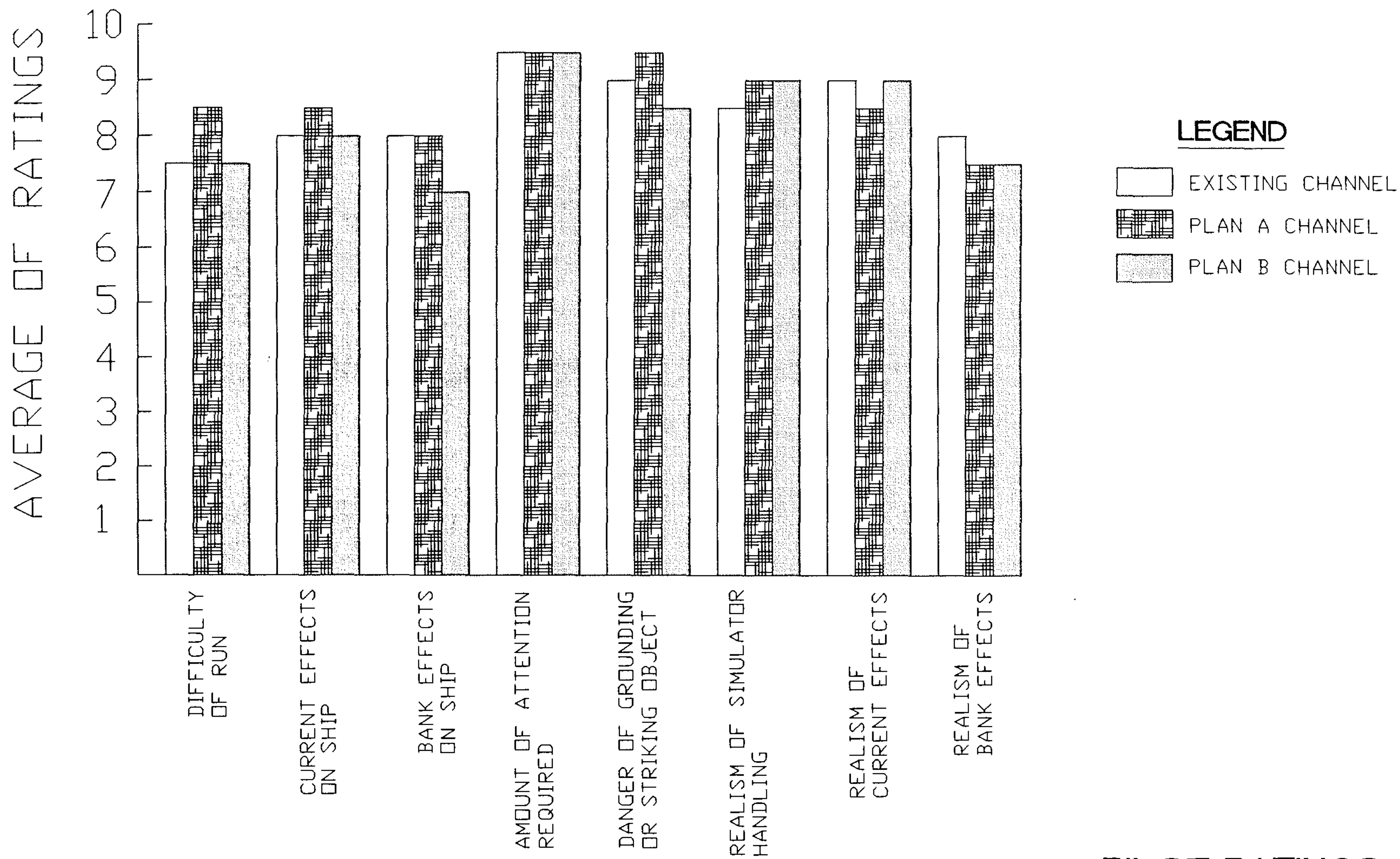
PILOT RATINGS

INBOUND, FORWARD RUNS

Plate 9

Plate 10

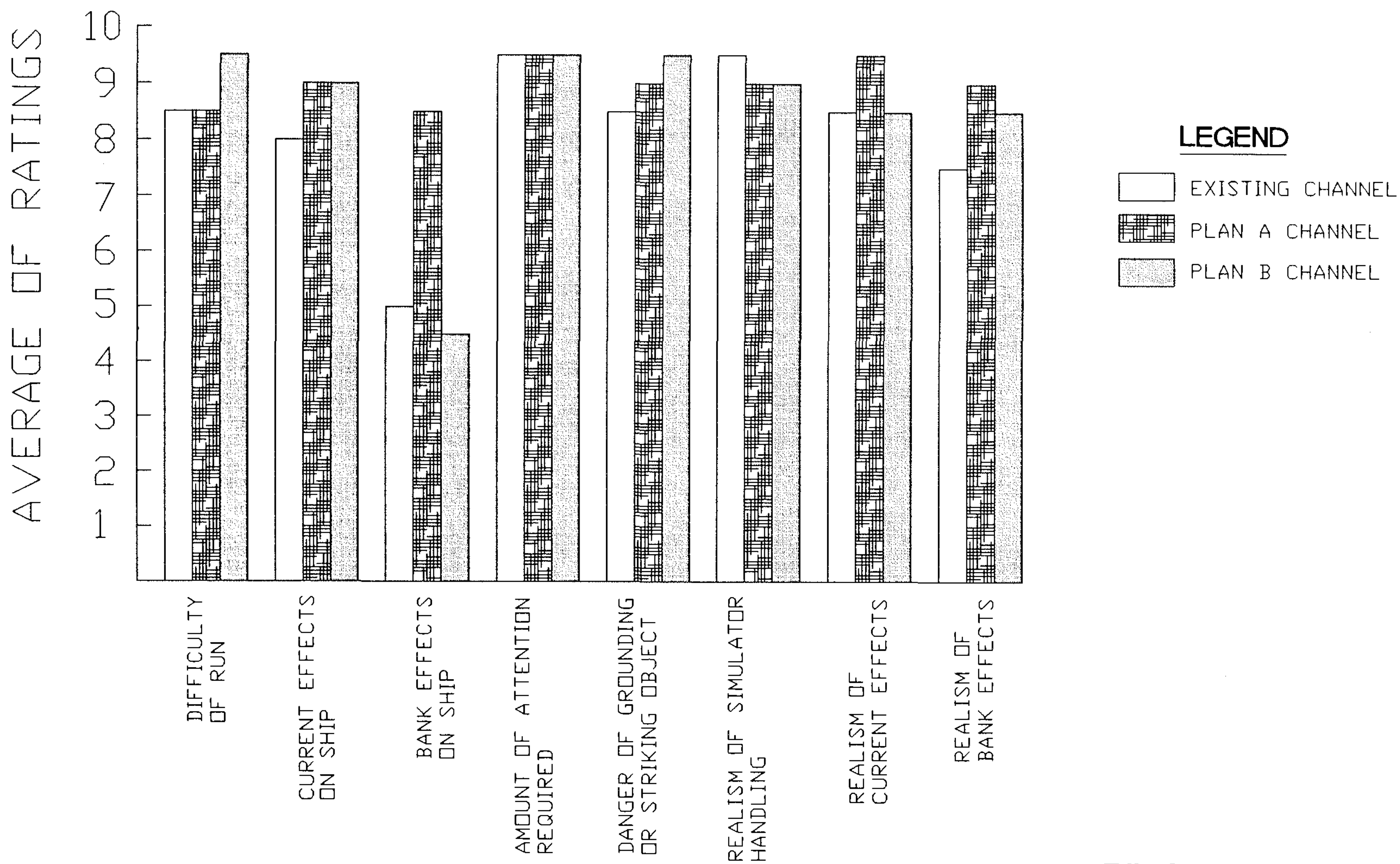

AVERAGE OF RATINGS
10
9
8
7
6
5
4
3
2
1
DIFFICULTY OF RUN
CURRENT EFFECTS ON SHIP
BANK EFFECTS ON SHIP
AMOUNT OF ATTENTION REQUIRED
DANGER OF GROUNDING OR STRIKING OBJECT
REALISM OF SIMULATOR HANDLING
REALISM OF CURRENT EFFECTS
REALISM OF BANK EFFECTS
LEGEND
EXISTING CHANNEL
PLAN A CHANNEL
PLAN B CHANNEL
PILOT RATINGS
INBOUND, BACKING RUNS



PILOT RATINGS
OUTBOUND, FORWARD RUNS

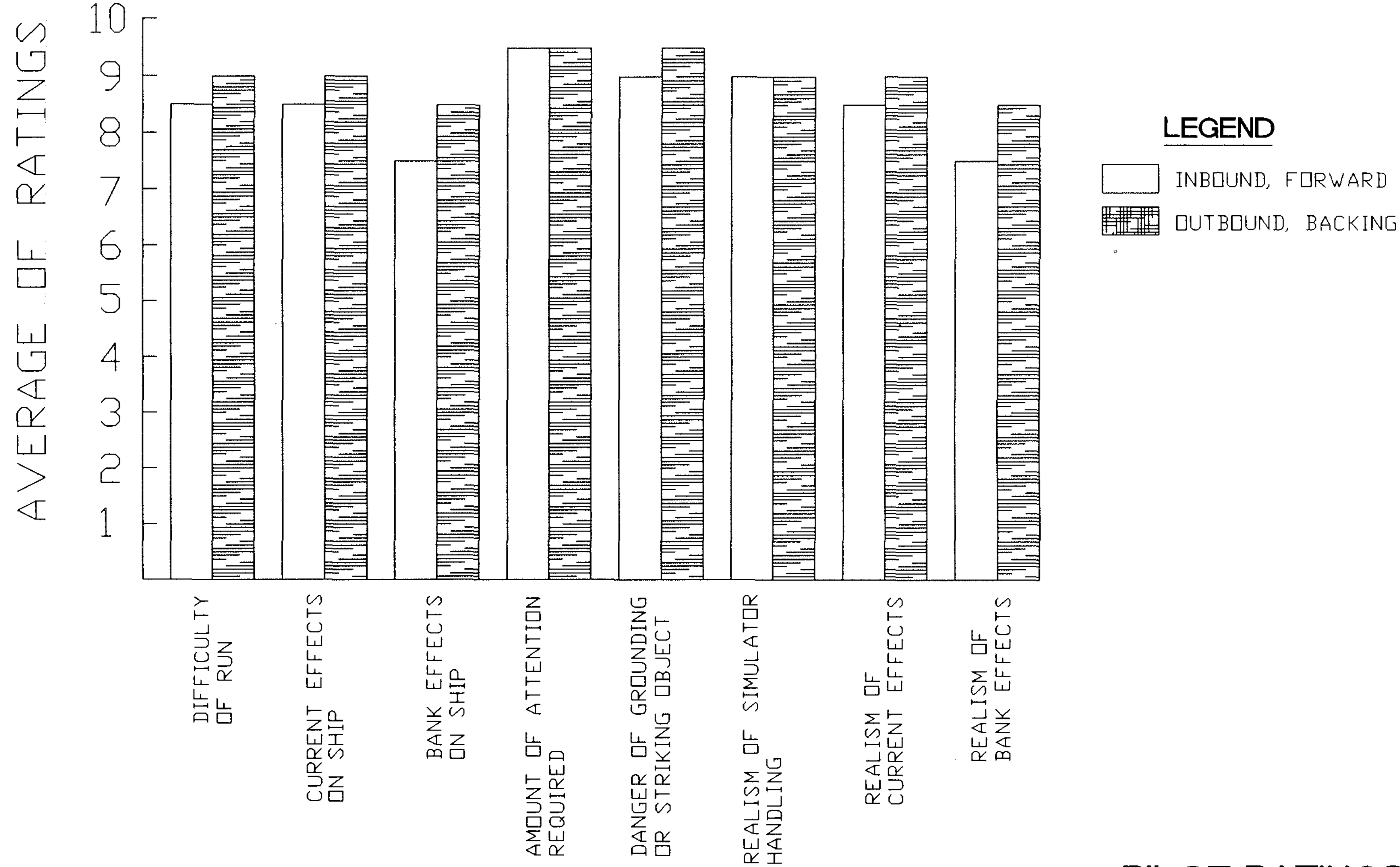
Plate 11

Plate 12



PILOT RATINGS

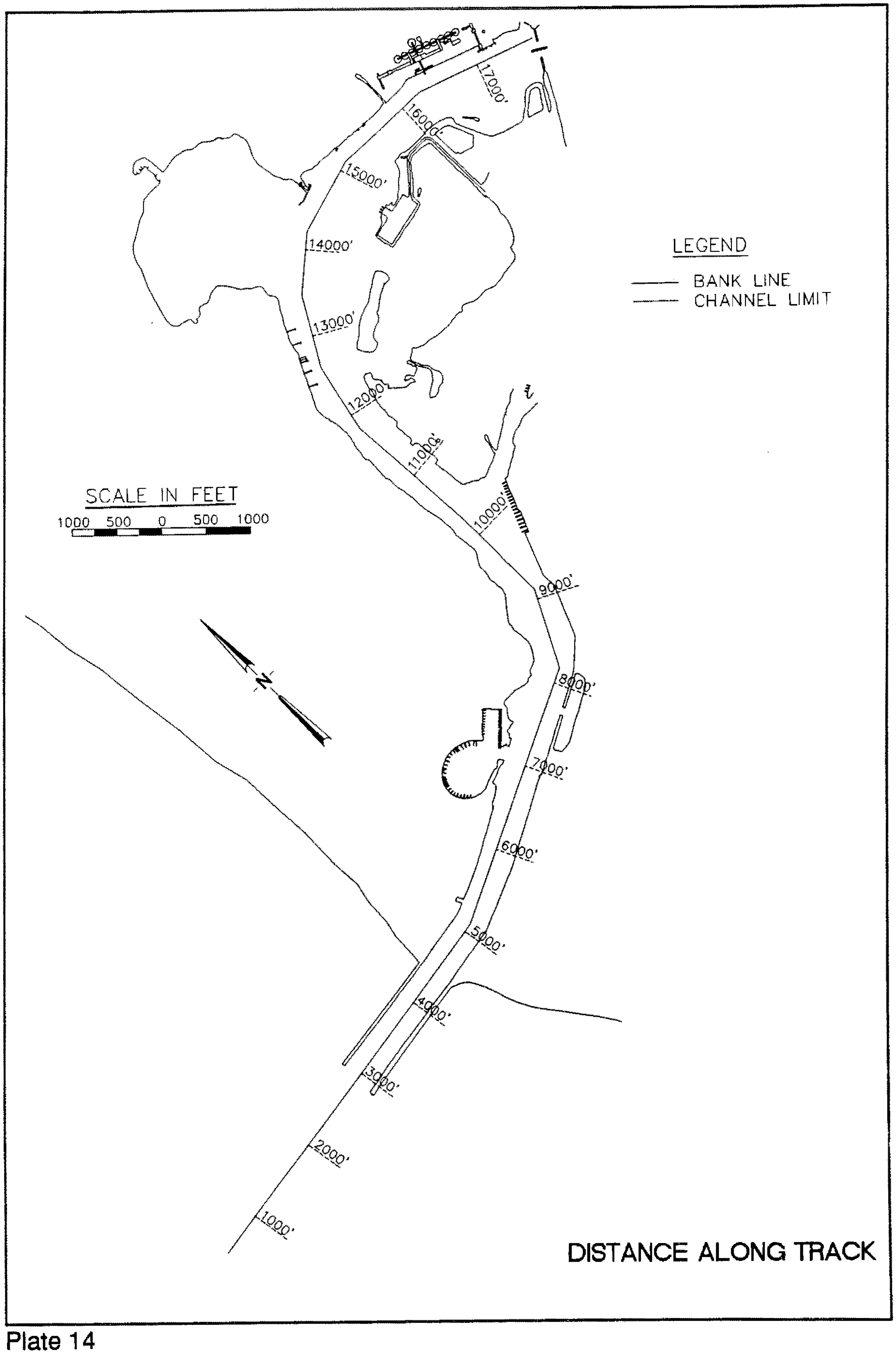
OUTBOUND, BACKING RUNS



PILOT RATINGS

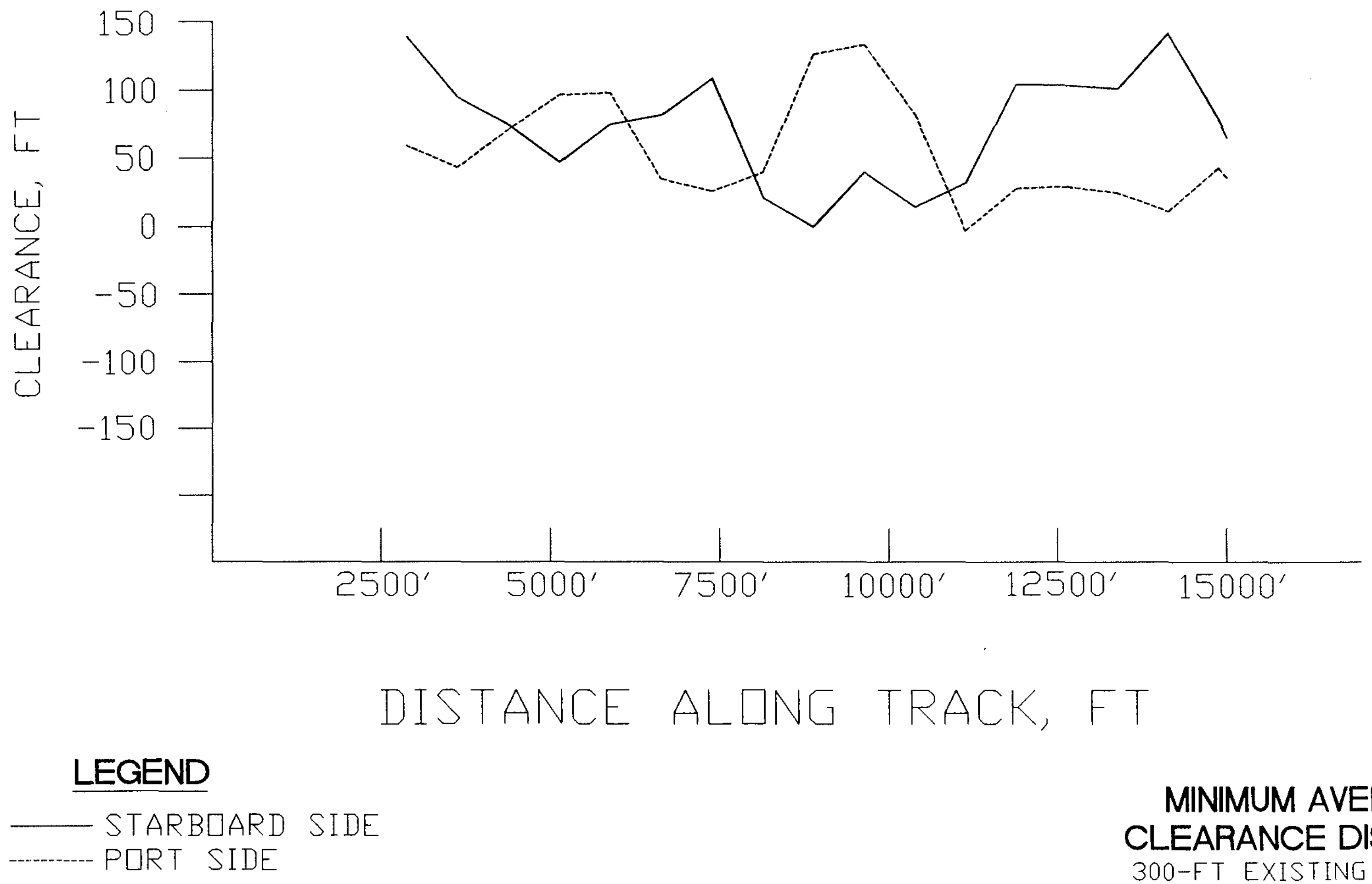
TURNING BASIN RUNS

Plate 13



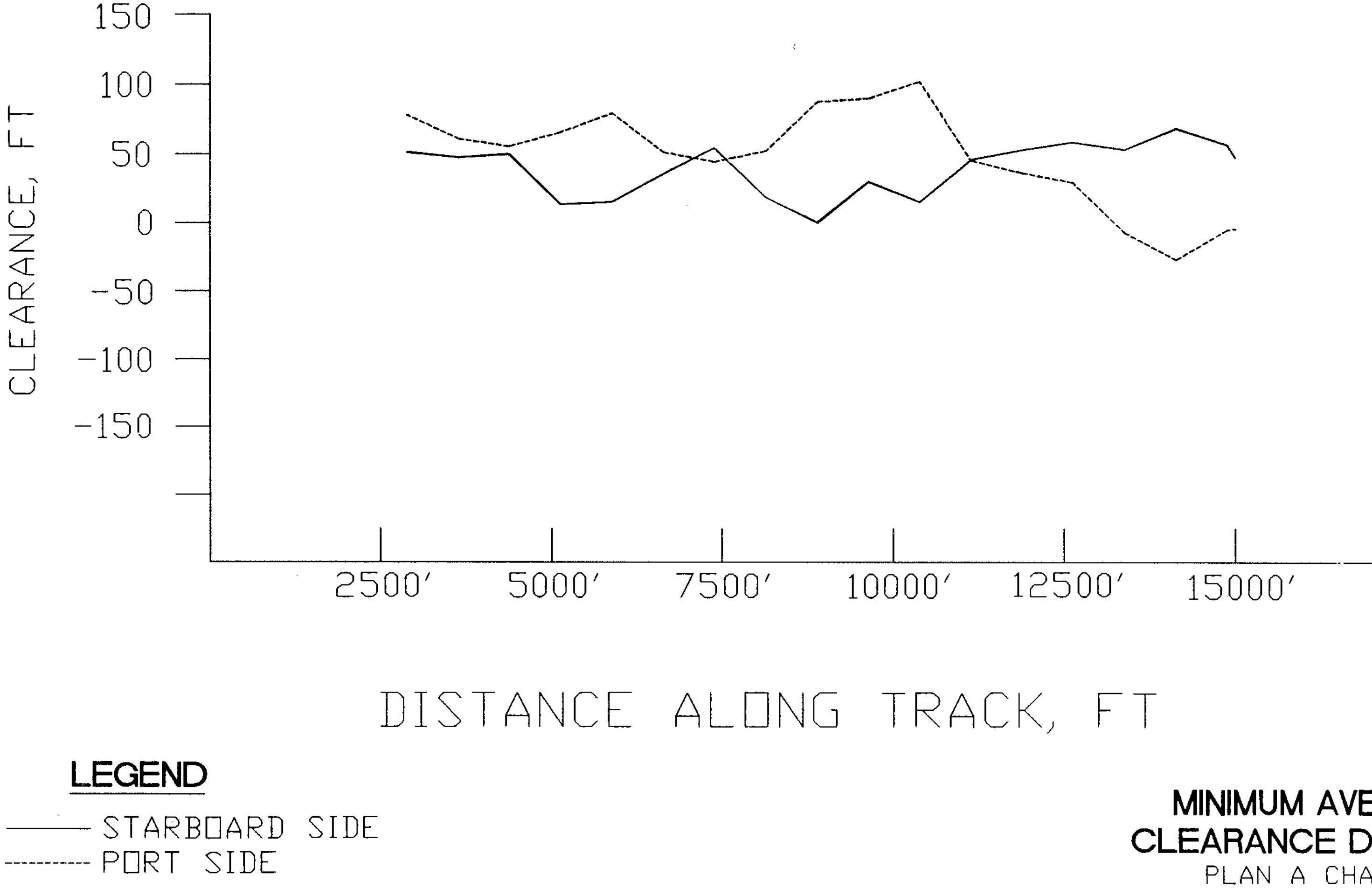
LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
17000'
16000'
15000'
14000'
13000'
12000'
11000'
10000'
9000'
8000'
7000'
6000'
5000'
4000'
3000'
2000'
1000'
DISTANCE ALONG TRACK

Plate 14

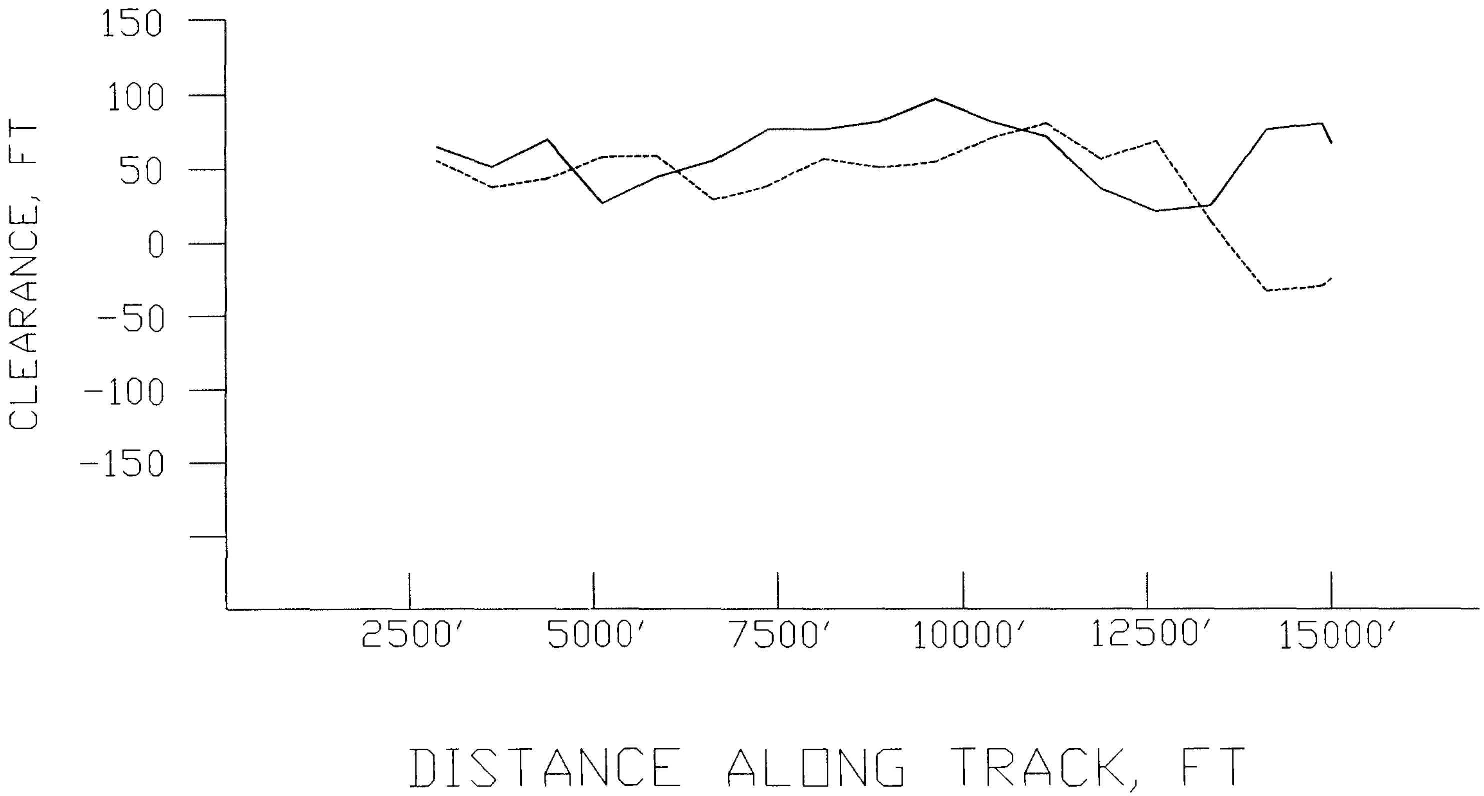


MINIMUM AVERAGE CLEARANCE DISTANCE
300-FT EXISTING CHANNEL
INBOUND, FORWARD
21-FT DRAFT

Plate 16



MINIMUM AVERAGE CLEARANCE DISTANCE
PLAN A CHANNEL
INBOUND, FORWARD
27-FT DRAFT



LEGEND

——— STARBOARD SIDE

-------- PORT SIDE

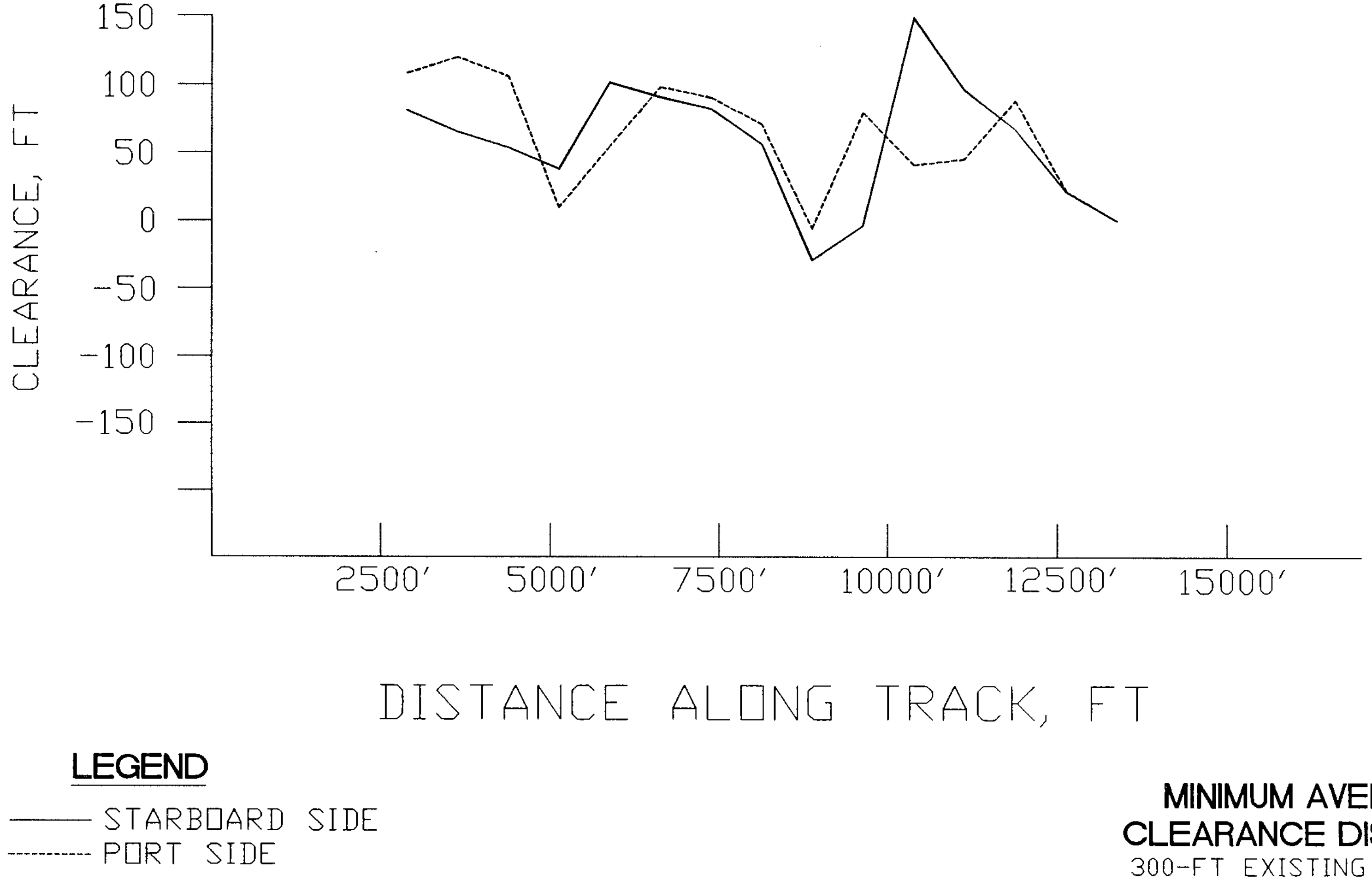
MINIMUM AVERAGE CLEARANCE DISTANCE

PLAN B CHANNEL

INBOUND, FORWARD

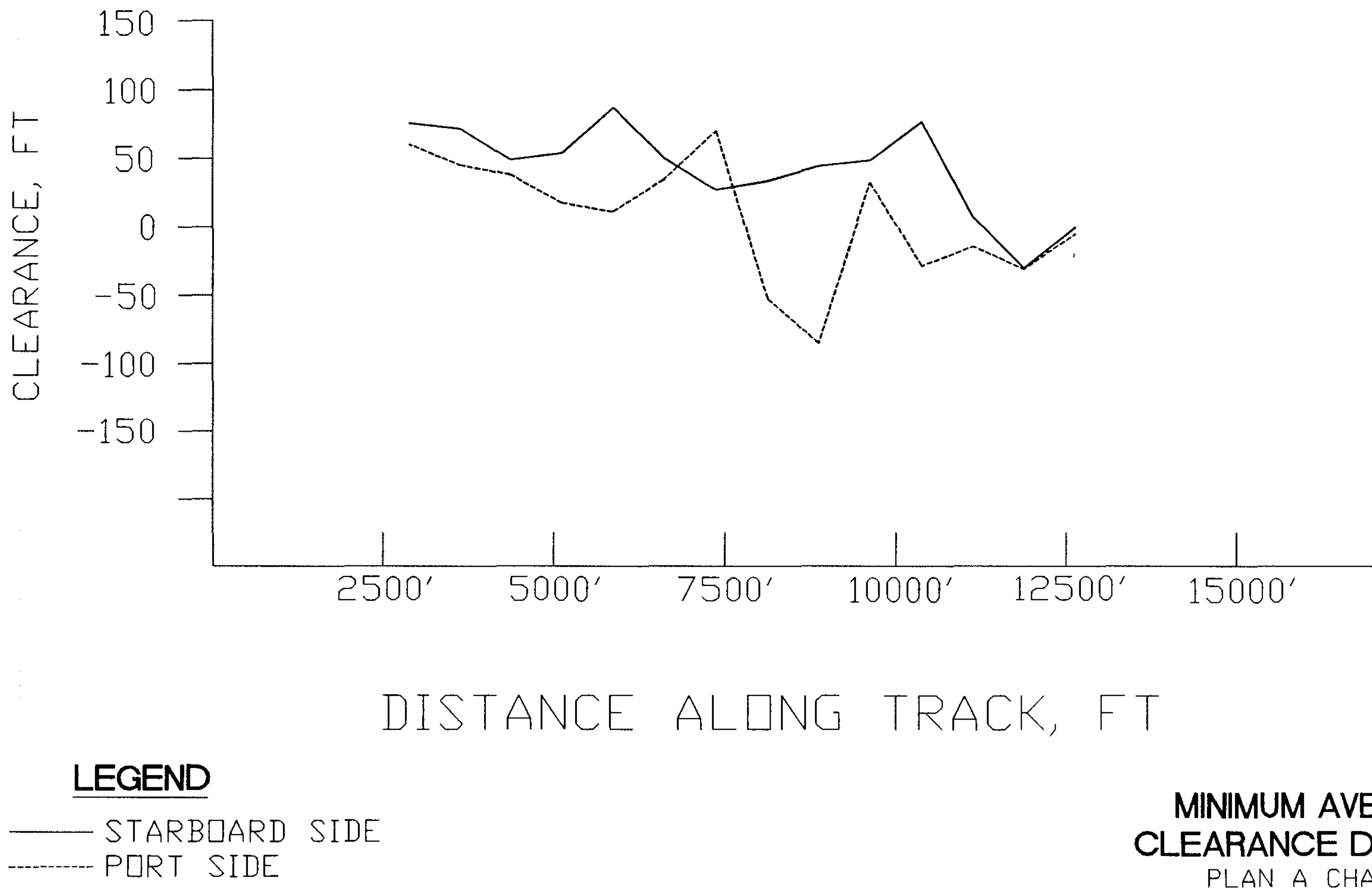
27-FT DRAFT

Plate 18



MINIMUM AVERAGE CLEARANCE DISTANCE

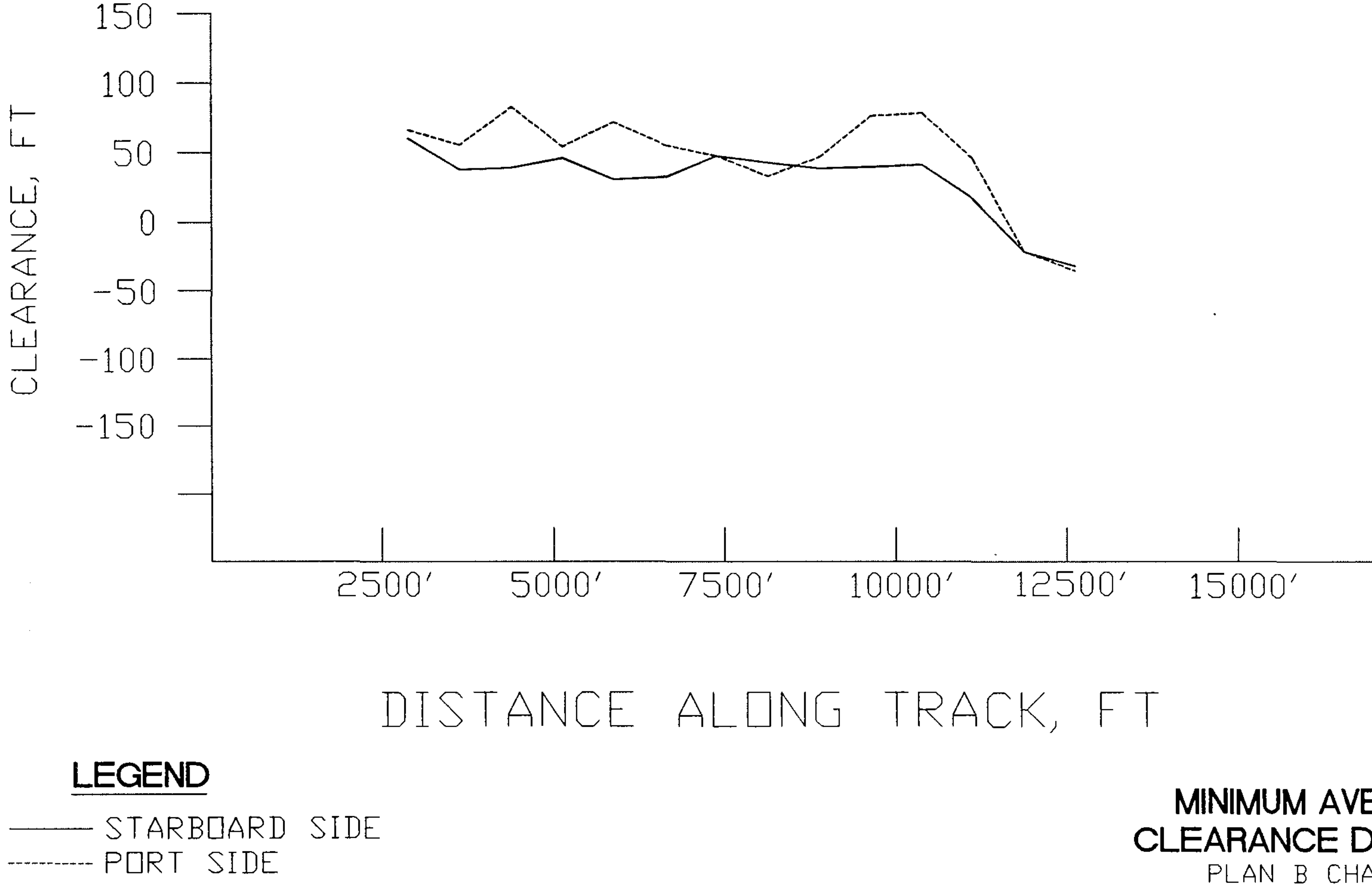
300-FT EXISTING CHANNEL
INBOUND, BACKING
18.5-FT DRAFT



MINIMUM AVERAGE CLEARANCE DISTANCE

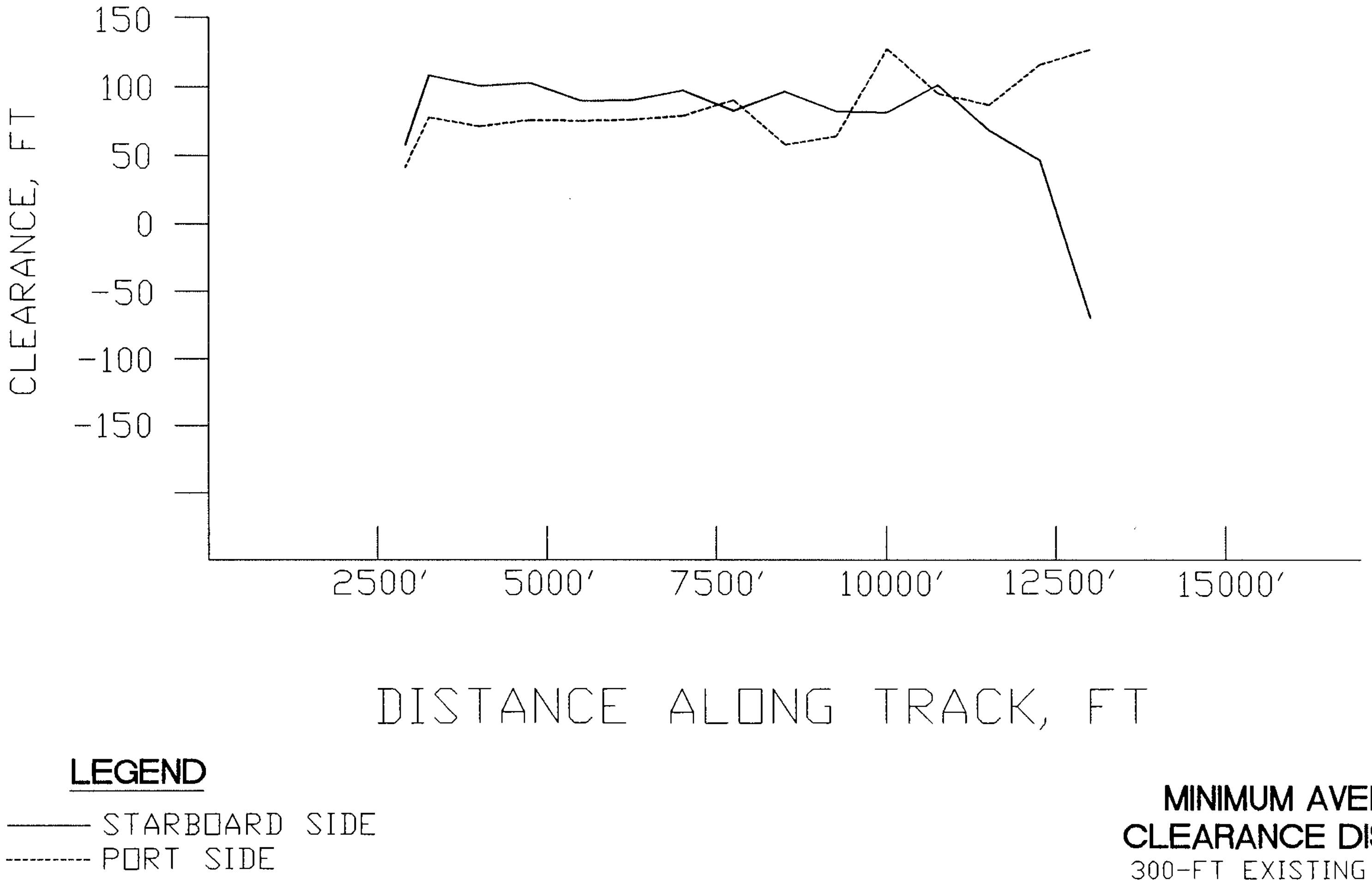
PLAN A CHANNEL
INBOUND, BACKING
18.5-FT DRAFT

Plate 20



MINIMUM AVERAGE CLEARANCE DISTANCE

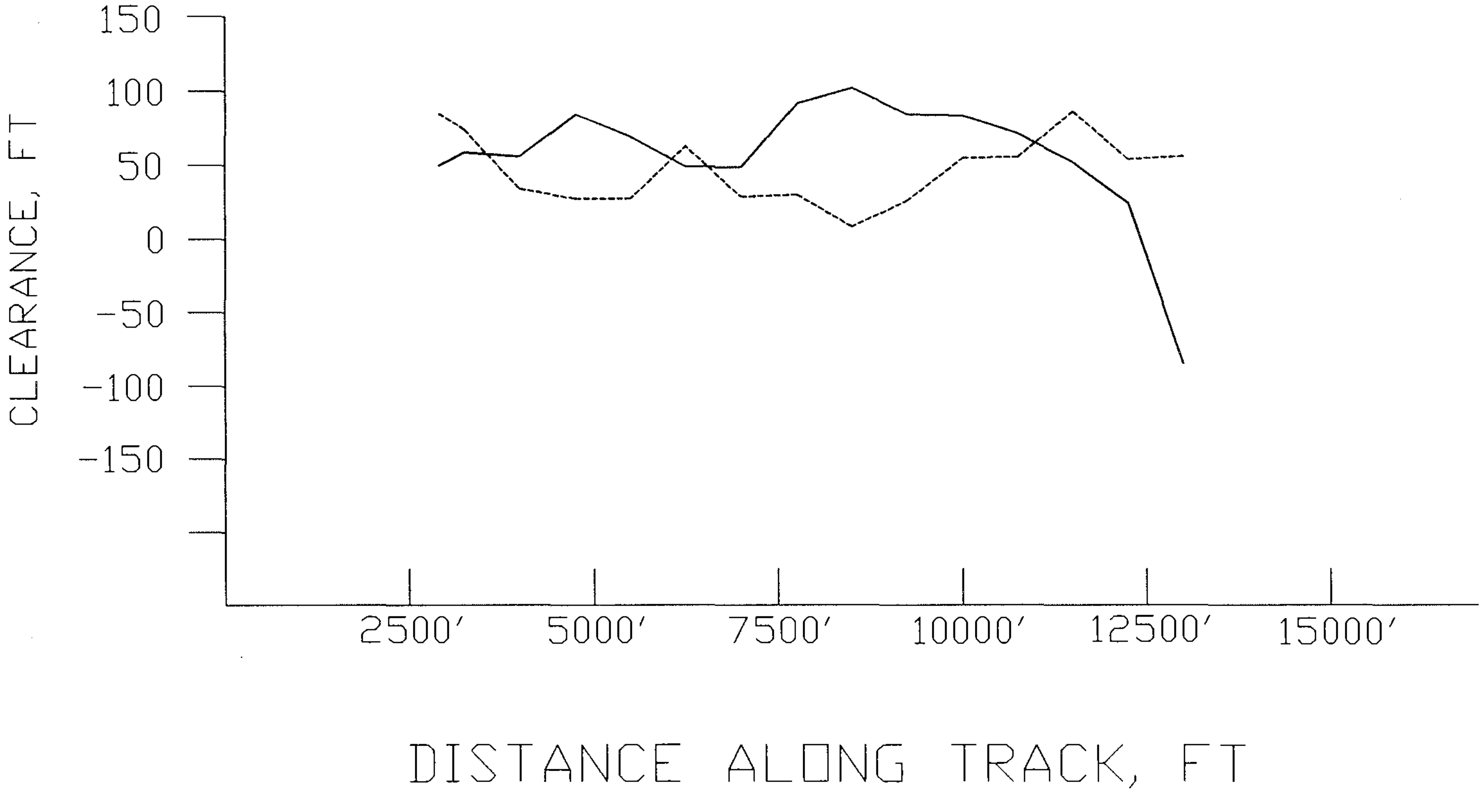
PLAN B CHANNEL
INBOUND, BACKING
18.5-FT DRAFT



MINIMUM AVERAGE CLEARANCE DISTANCE

300-FT EXISTING CHANNEL
OUTBOUND, FORWARD
21-FT DRAFT

Plate 22

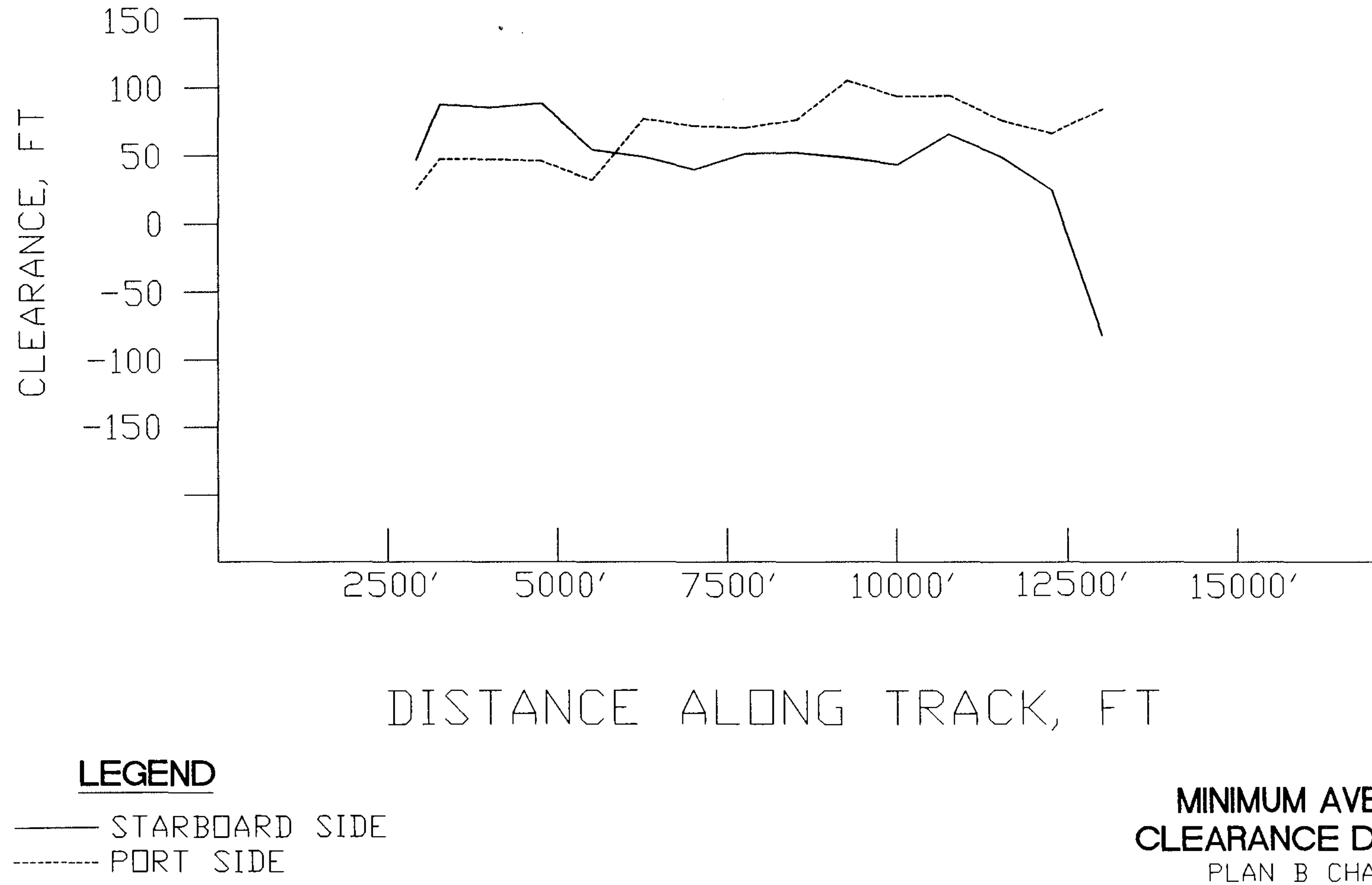


LEGEND

——— STARBOARD SIDE
- - - - - PORT SIDE

MINIMUM AVERAGE CLEARANCE DISTANCE

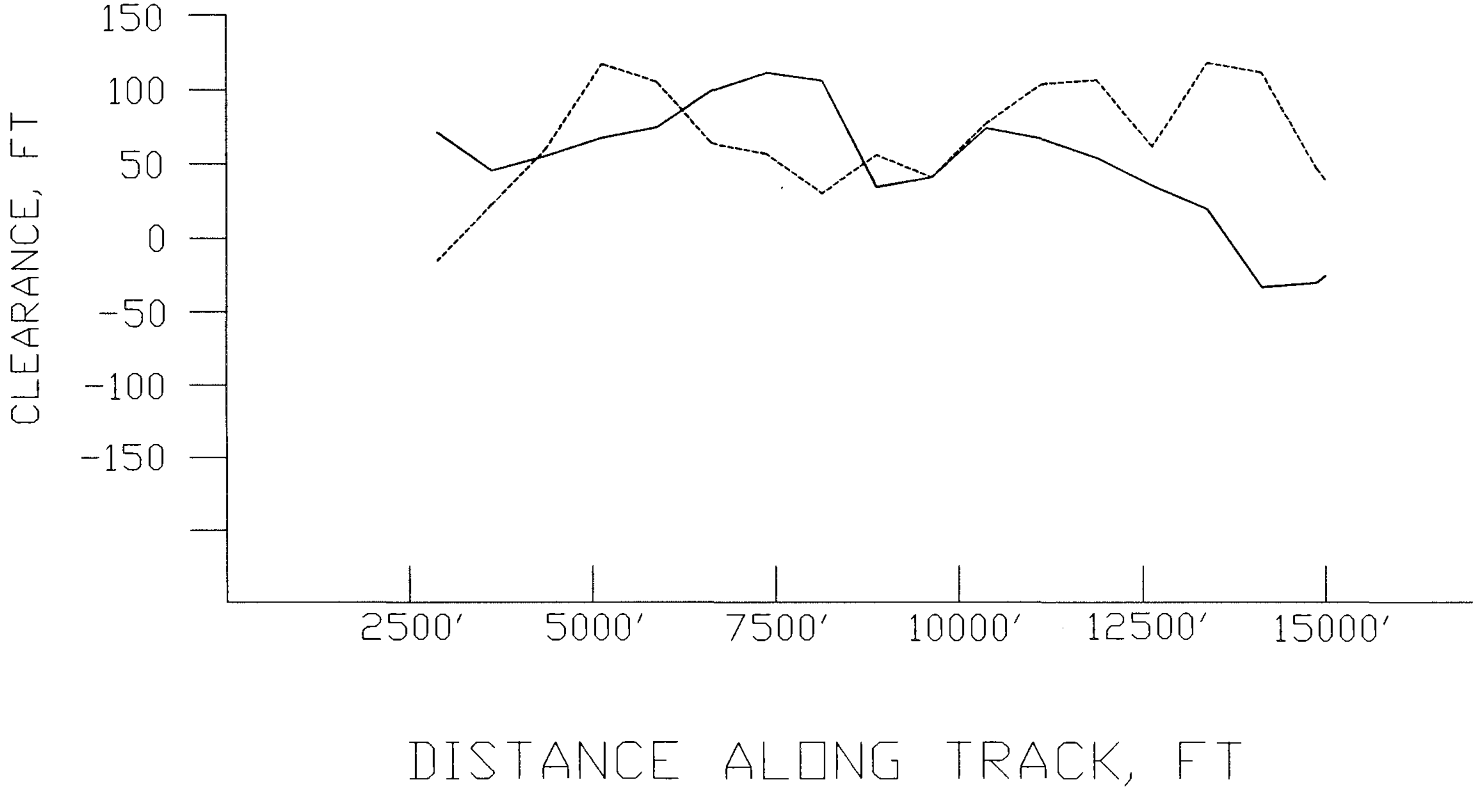
PLAN A CHANNEL
OUTBOUND, FORWARD
27-FT DRAFT



MINIMUM AVERAGE CLEARANCE DISTANCE

PLAN B CHANNEL
OUTBOUND, FORWARD
27-FT DRAFT

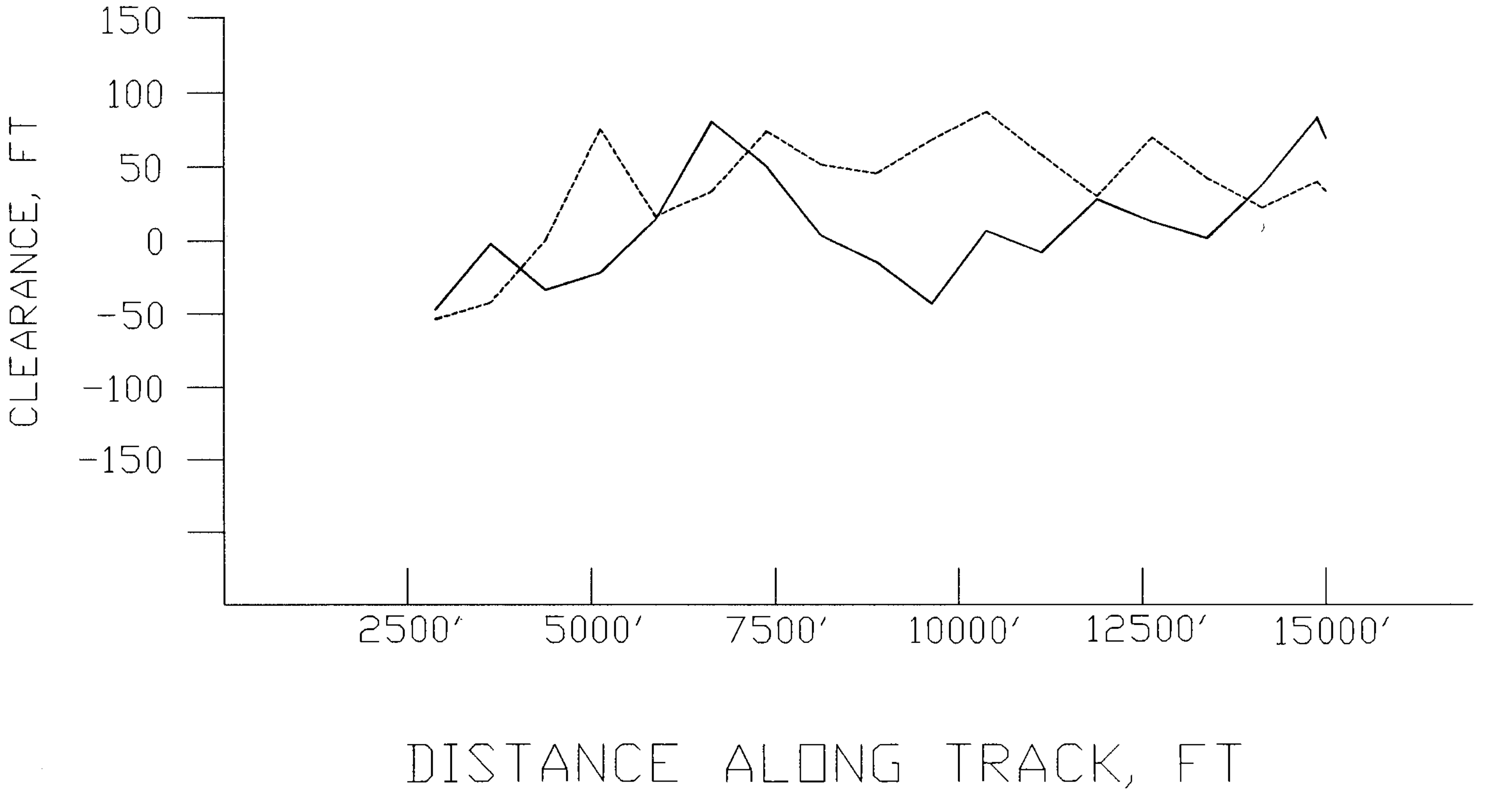
Plate 24



LEGEND

——— STARBOARD SIDE
------- PORT SIDE

MINIMUM AVERAGE CLEARANCE DISTANCE
300-FT EXISTING CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT

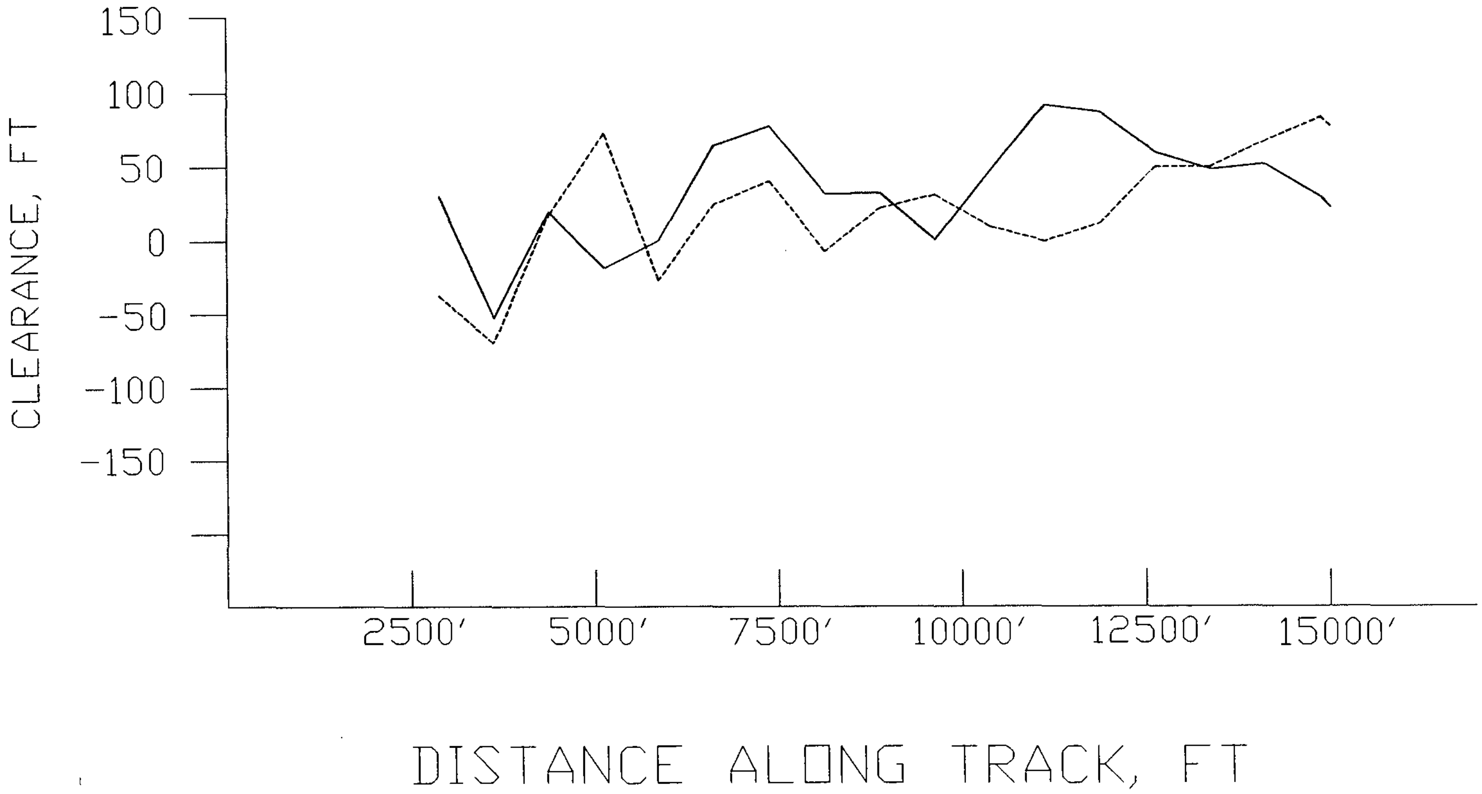


LEGEND

——— STARBOARD SIDE
------- PORT SIDE

MINIMUM AVERAGE CLEARANCE DISTANCE

PLAN A CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT

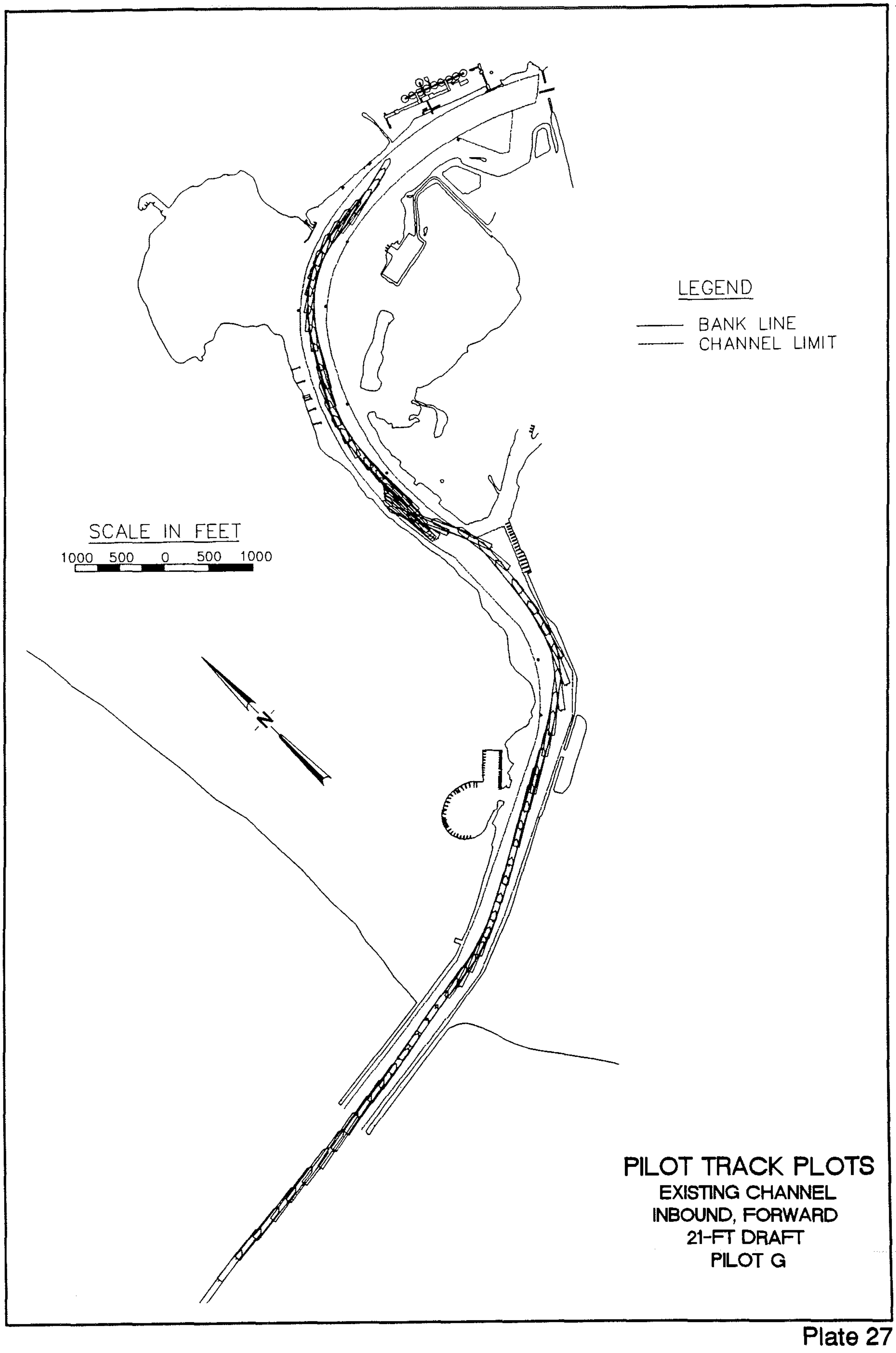


LEGEND

——— STARBOARD SIDE
- - - - - PORT SIDE

MINIMUM AVERAGE CLEARANCE DISTANCE

PLAN B CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT


LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
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N
PILOT TRACK PLOTS
EXISTING CHANNEL
INBOUND, FORWARD
21-FT DRAFT
PILOT G

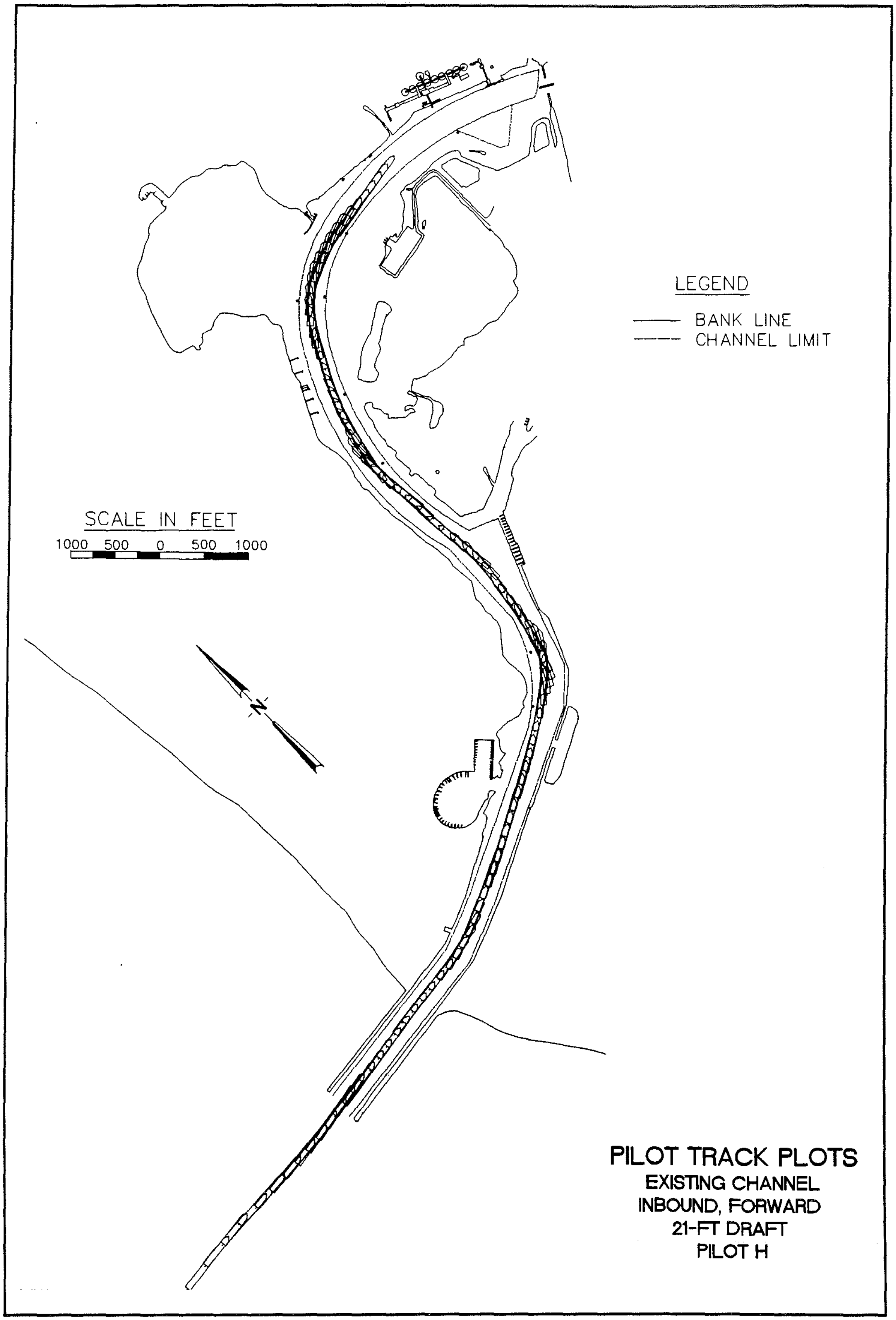
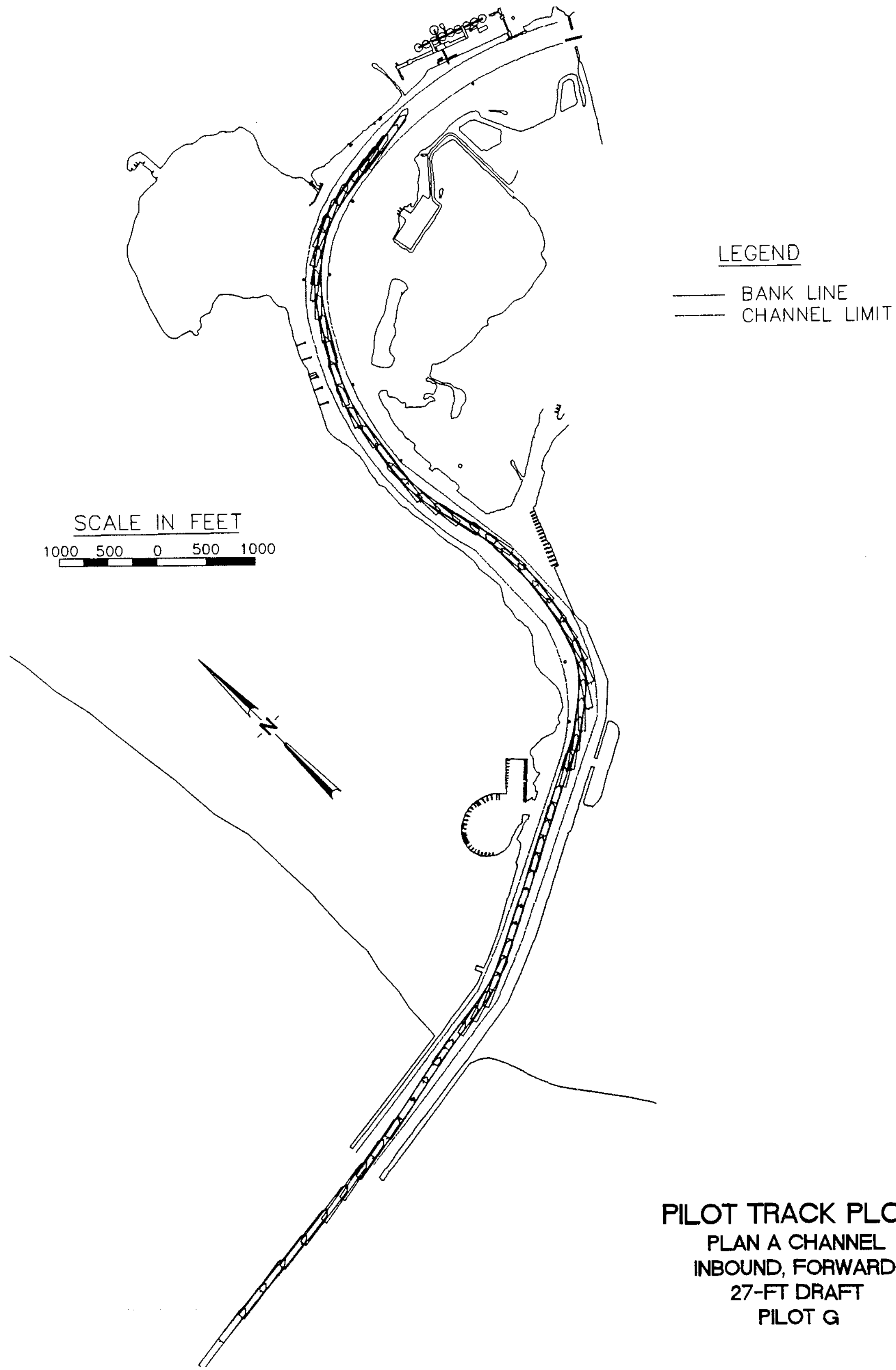
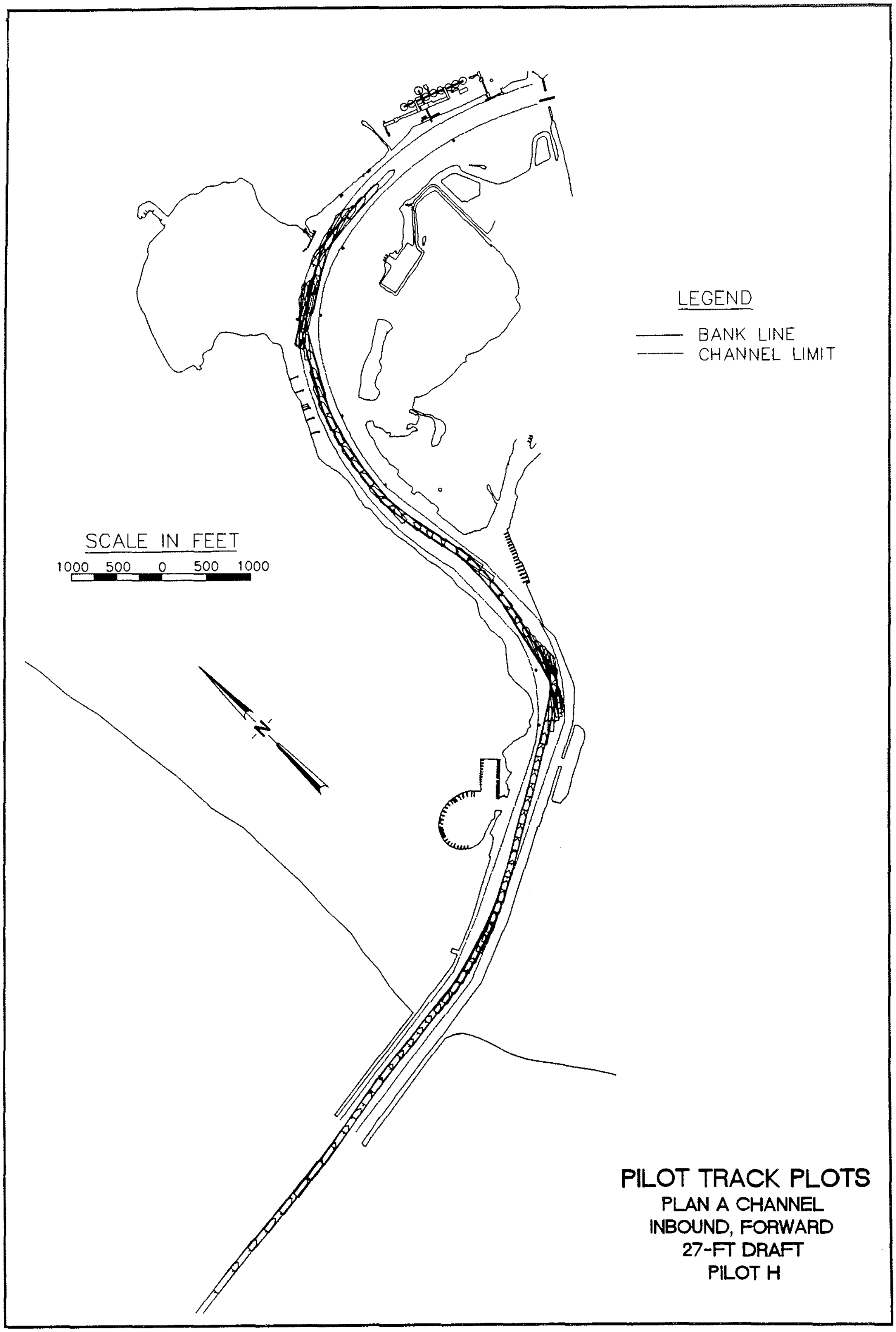
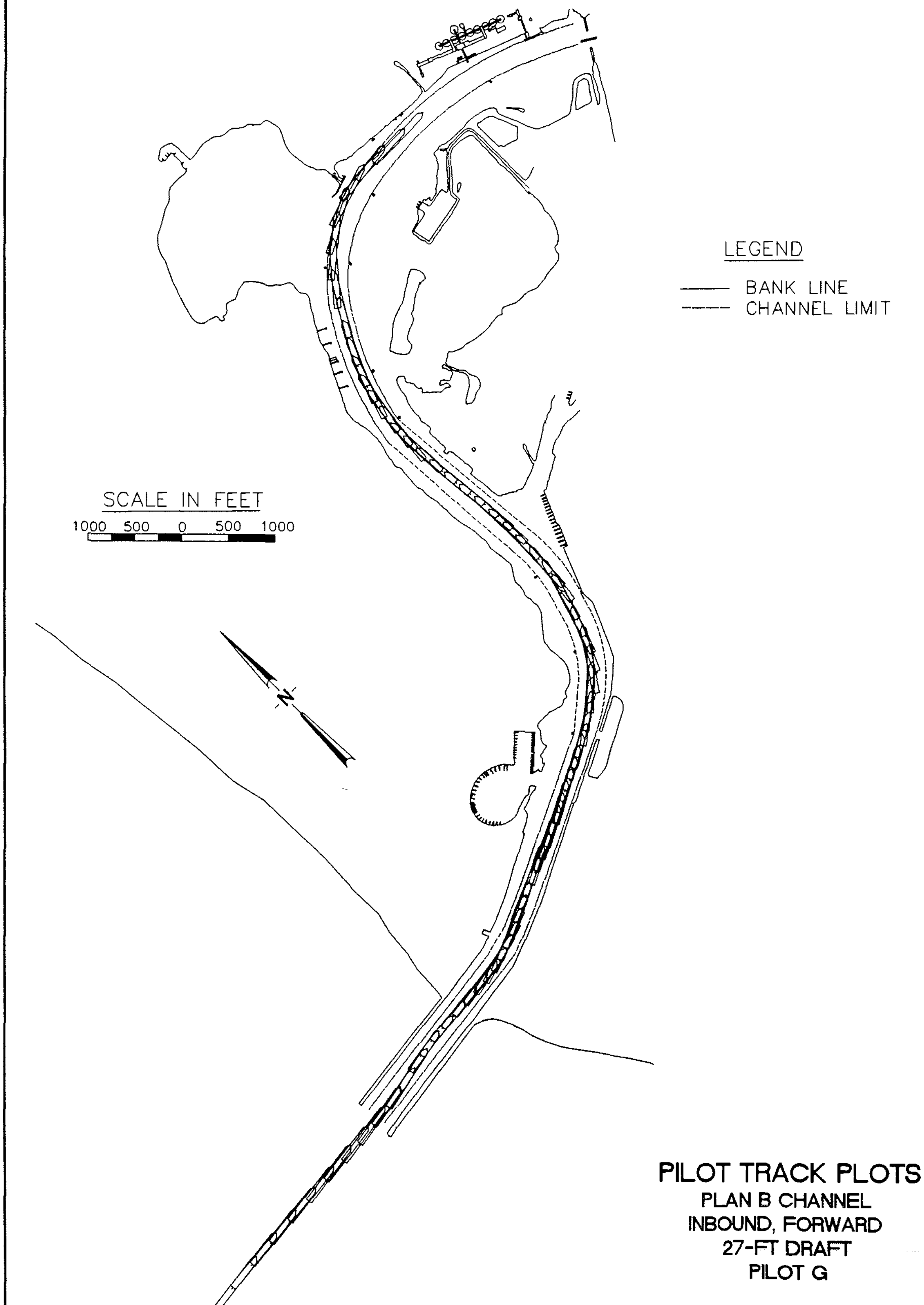

LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
PILOT TRACK PLOTS
EXISTING CHANNEL
INBOUND, FORWARD
21-FT DRAFT
PILOT H

Plate 28

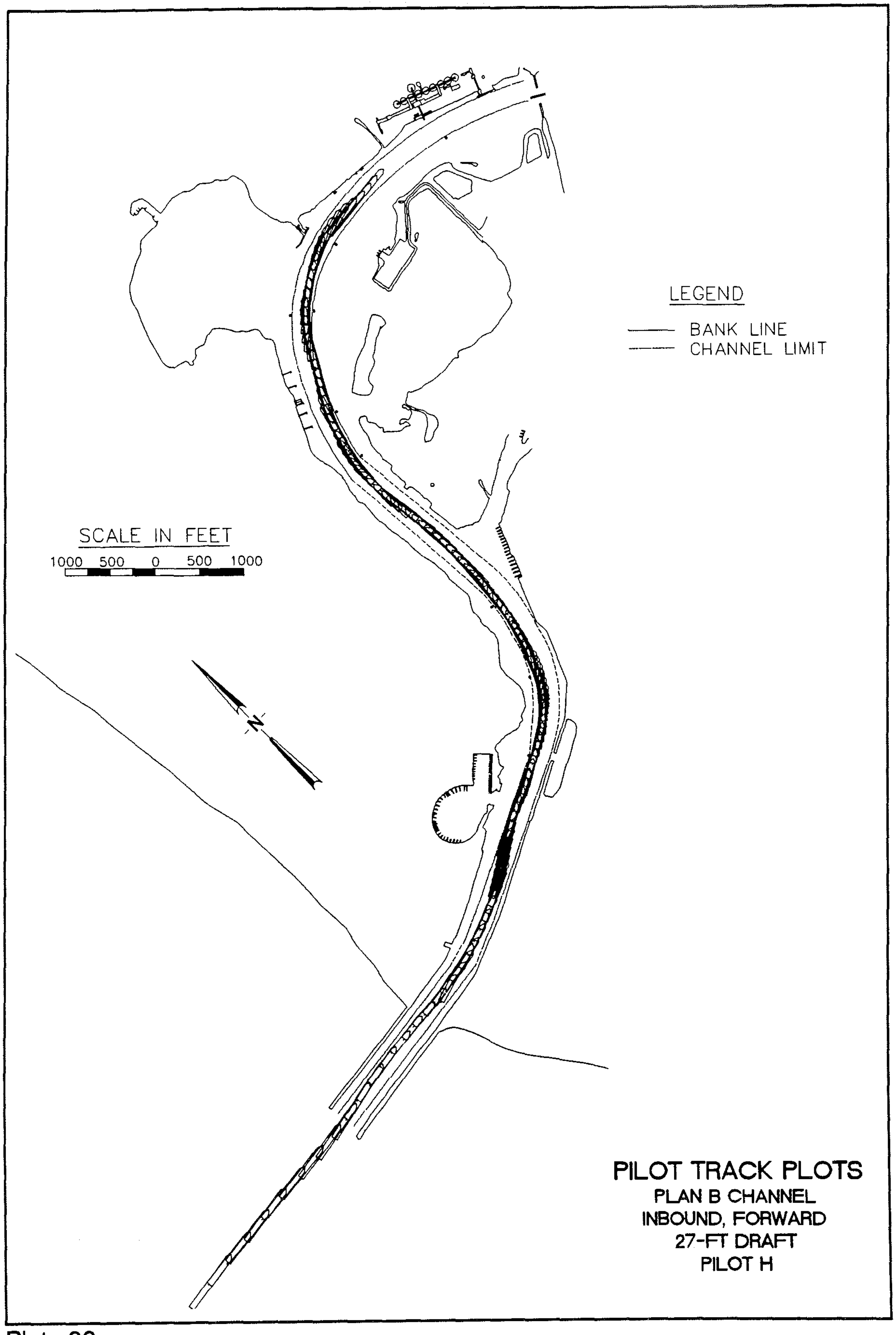


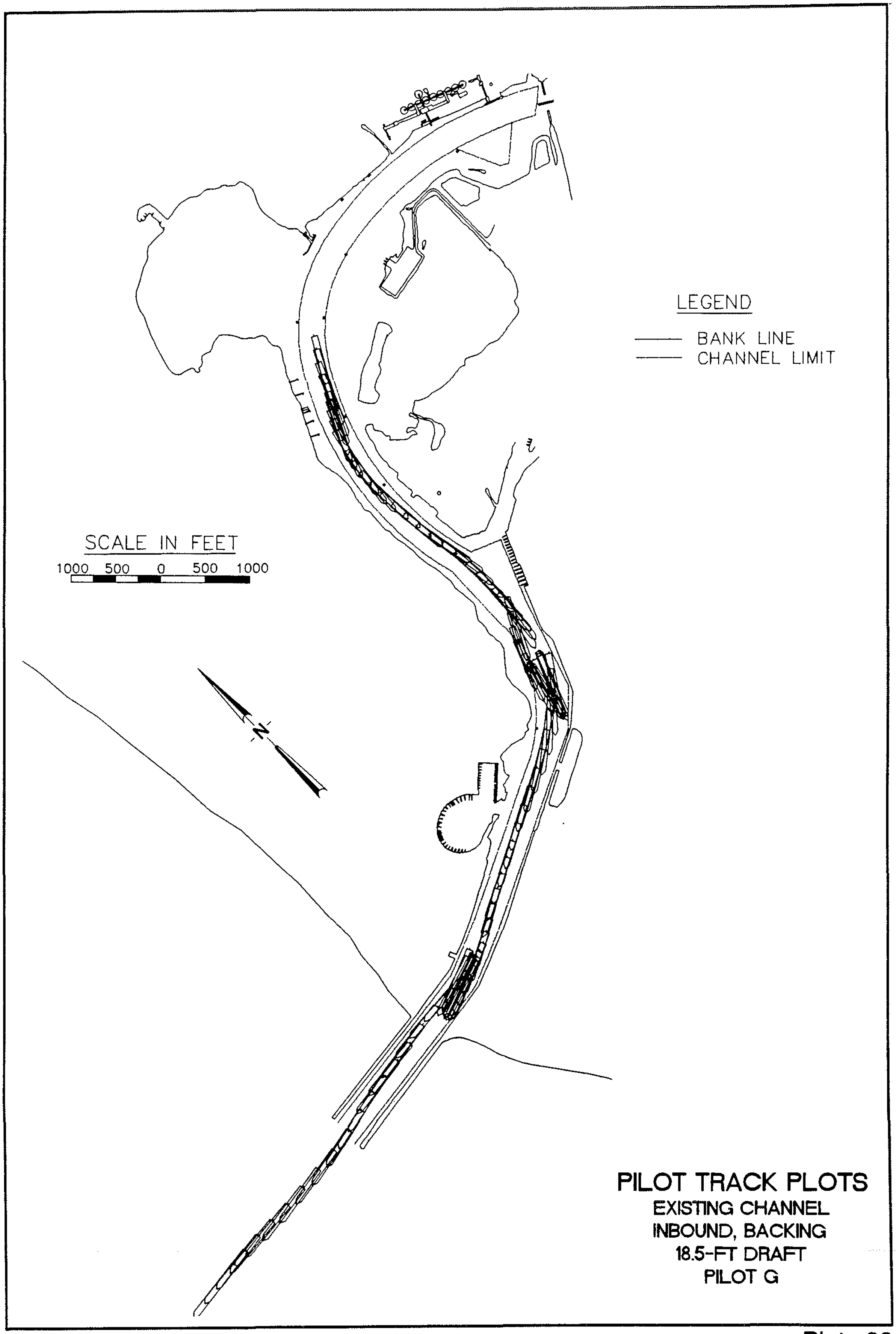
PILOT TRACK PLOTS
PLAN A CHANNEL
INBOUND, FORWARD
27-FT DRAFT
PILOT G


LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
PILOT TRACK PLOTS
PLAN A CHANNEL
INBOUND, FORWARD
27-FT DRAFT
PILOT H



PILOT TRACK PLOTS
PLAN B CHANNEL
INBOUND, FORWARD
27-FT DRAFT
PILOT G


LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
PILOT TRACK PLOTS
PLAN B CHANNEL
INBOUND, FORWARD
27-FT DRAFT
PILOT H


LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
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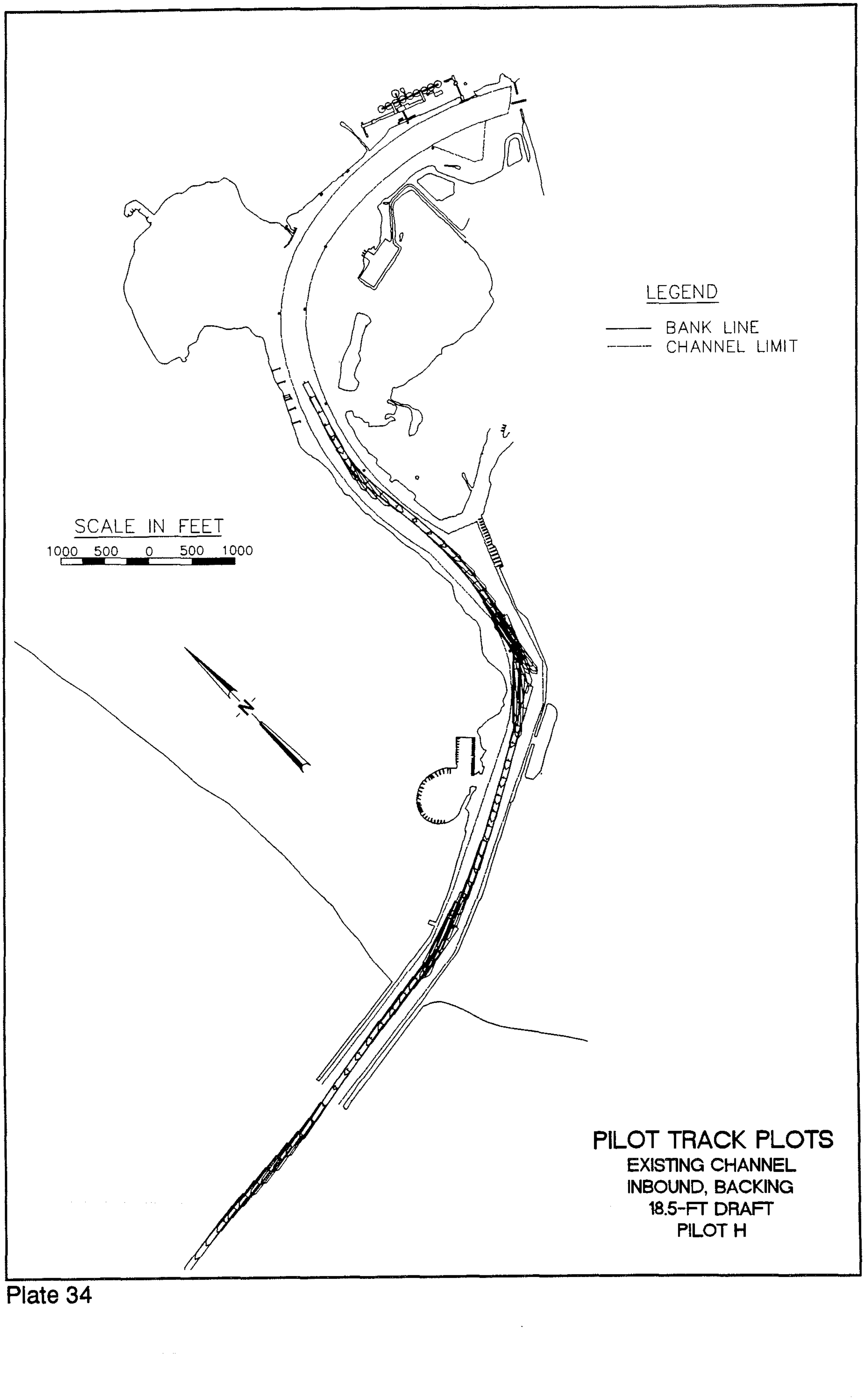
N
PILOT TRACK PLOTS
EXISTING CHANNEL
INBOUND, BACKING
18.5-FT DRAFT
PILOT G


LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
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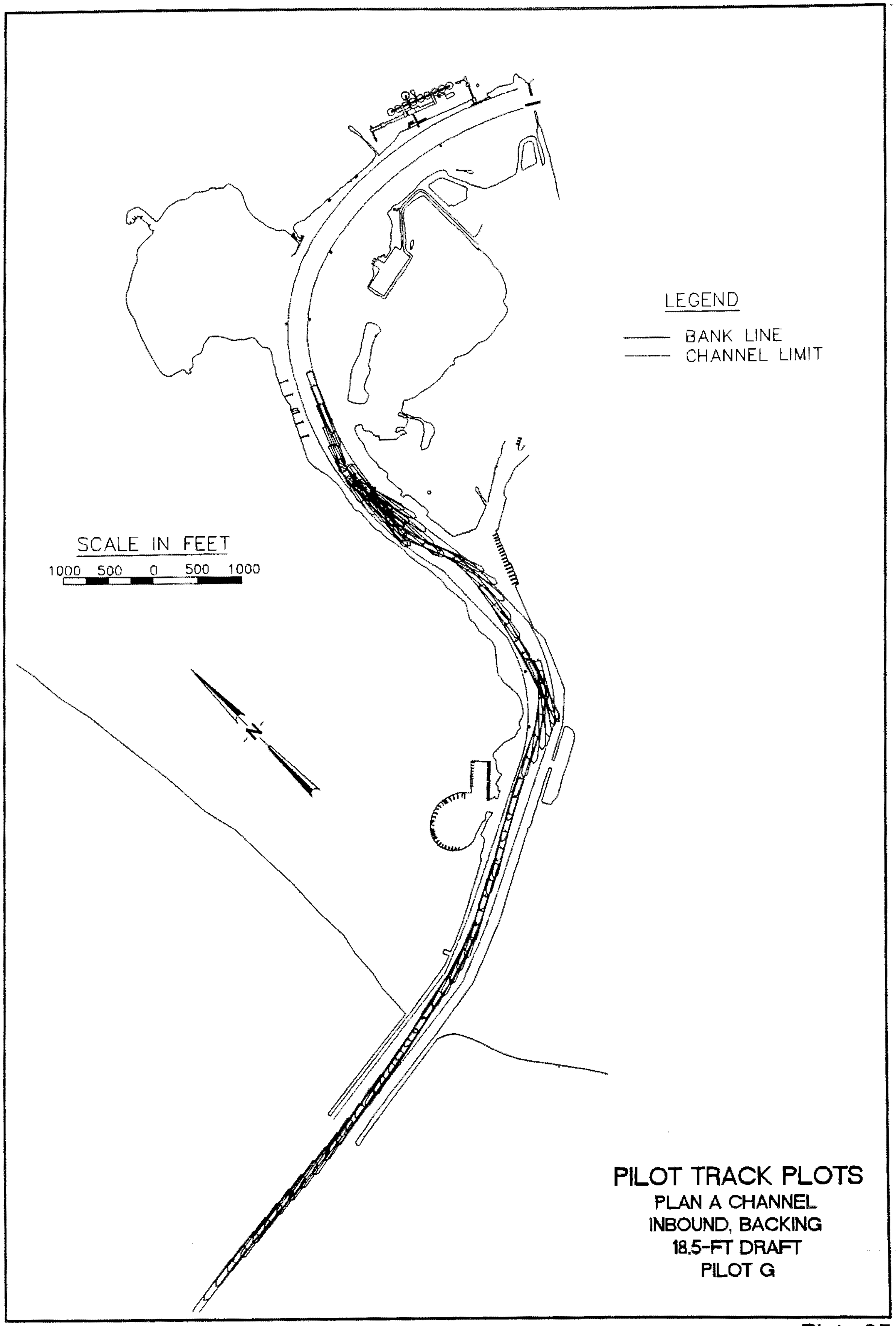
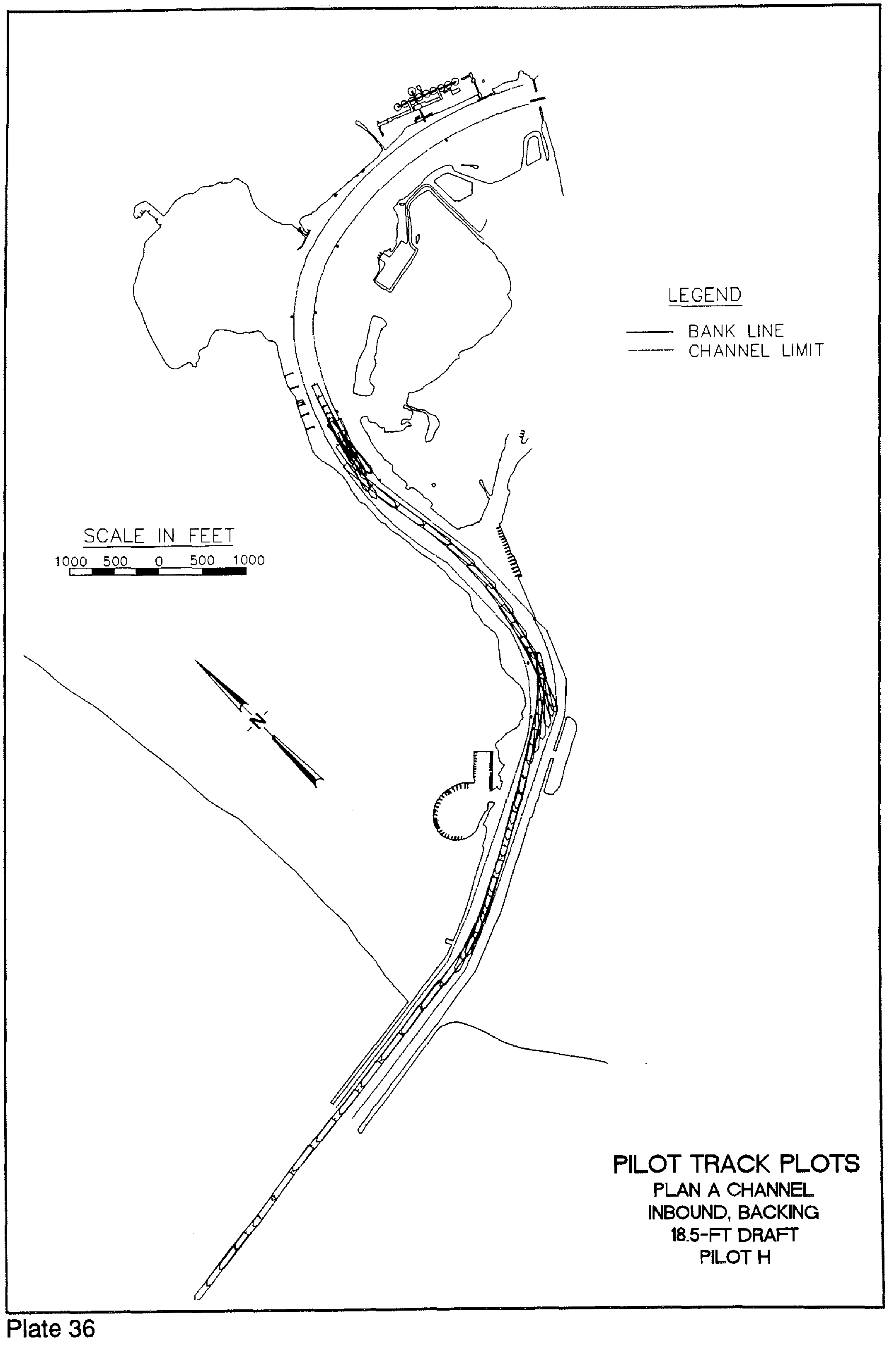
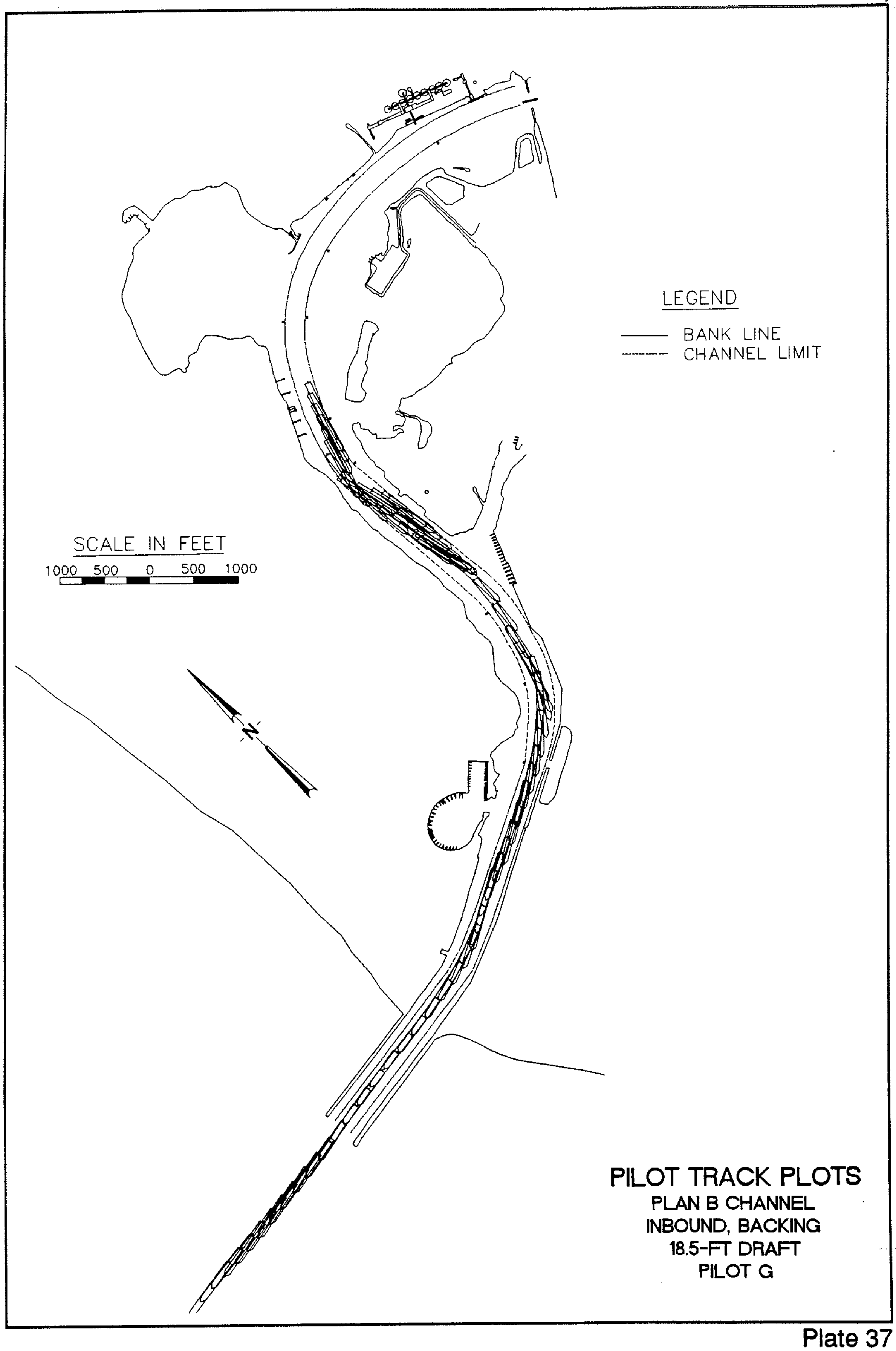
N
PILOT TRACK PLOTS
EXISTING CHANNEL
INBOUND, BACKING
18.5-FT DRAFT
PILOT H

Plate 34


LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
PILOT TRACK PLOTS
PLAN A CHANNEL
INBOUND, BACKING
18.5-FT DRAFT
PILOT G


LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
PILOT TRACK PLOTS
PLAN A CHANNEL
INBOUND, BACKING
18.5-FT DRAFT
PILOT H



LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
PILOT TRACK PLOTS
PLAN B CHANNEL
INBOUND, BACKING
18.5-FT DRAFT
PILOT G

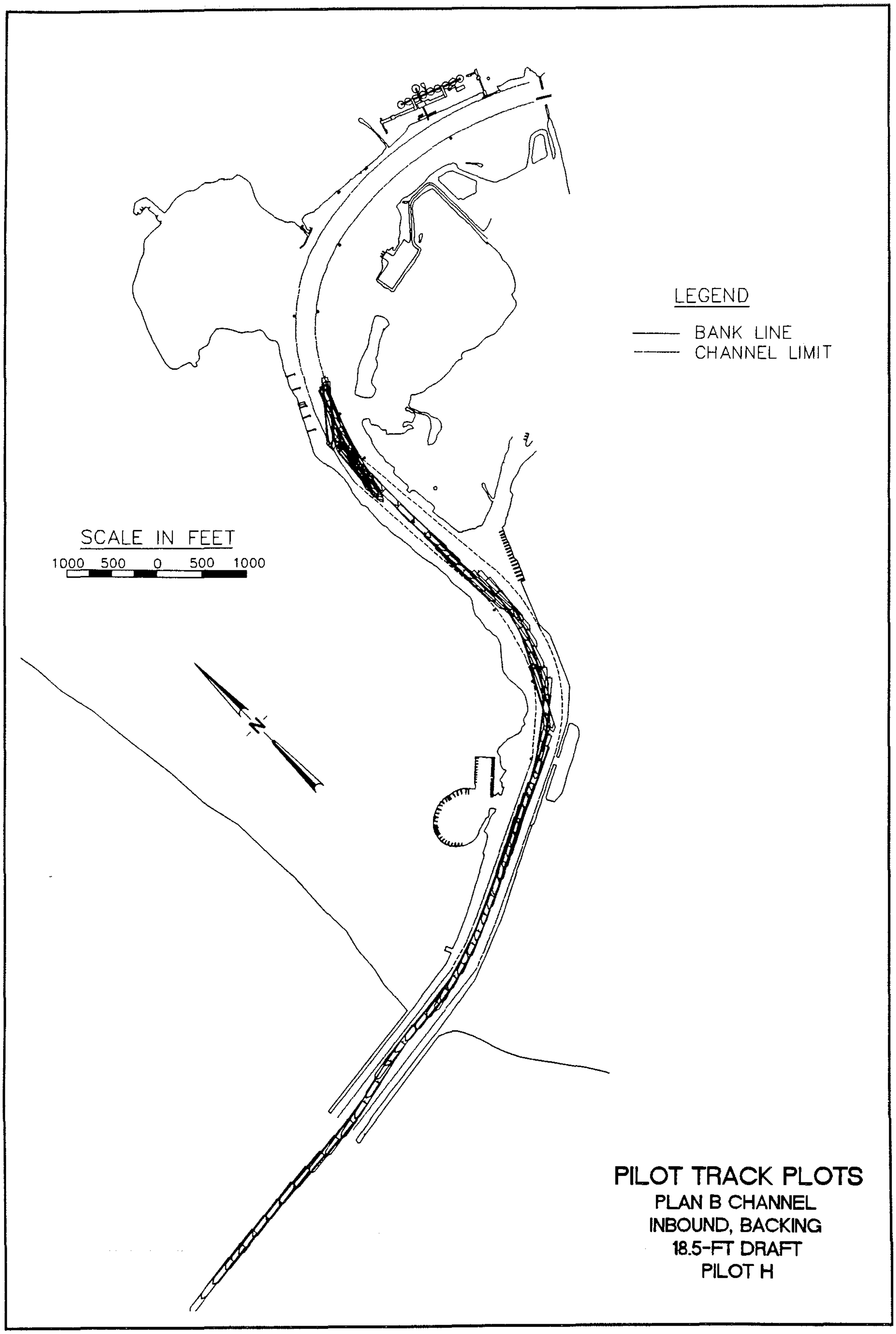
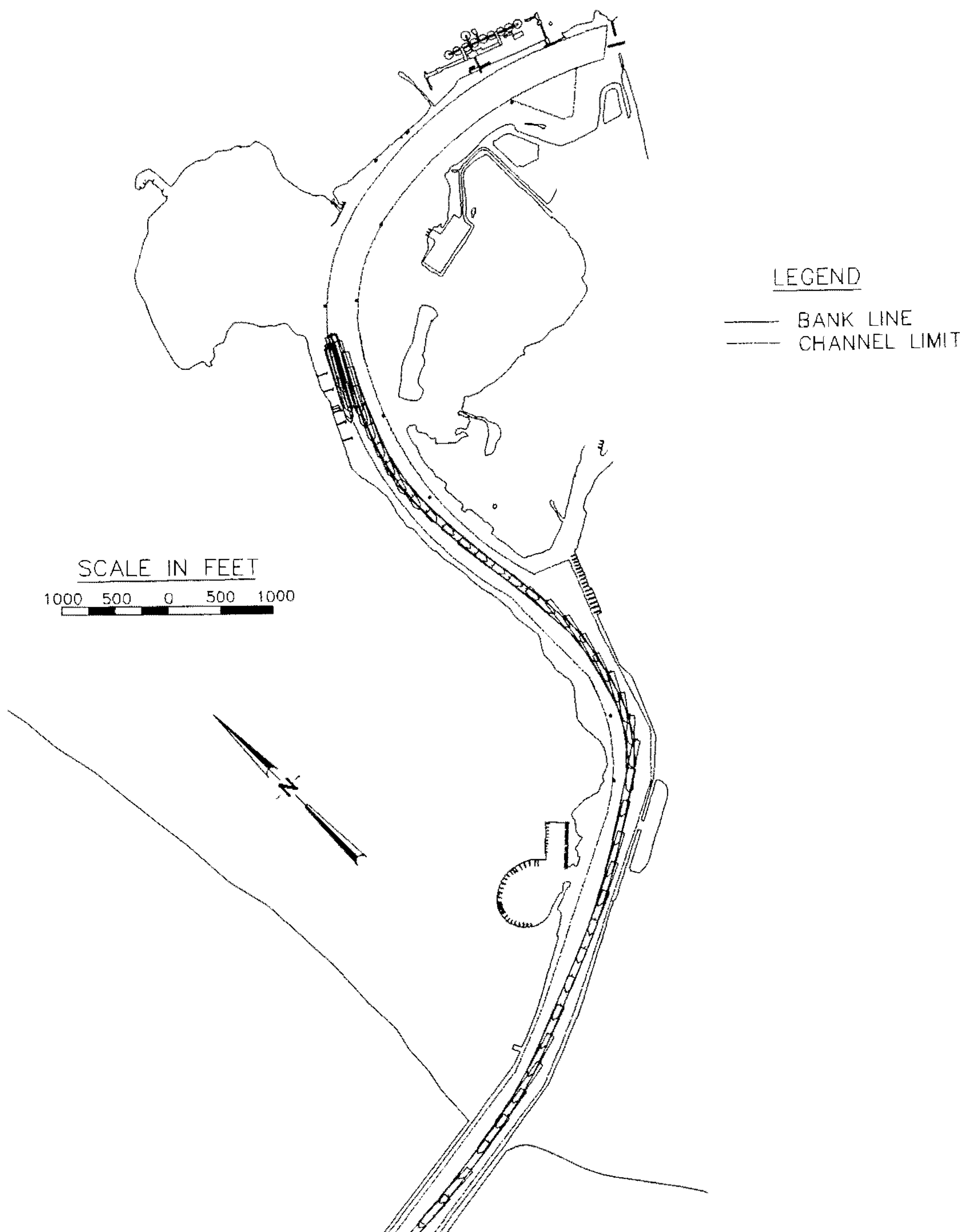
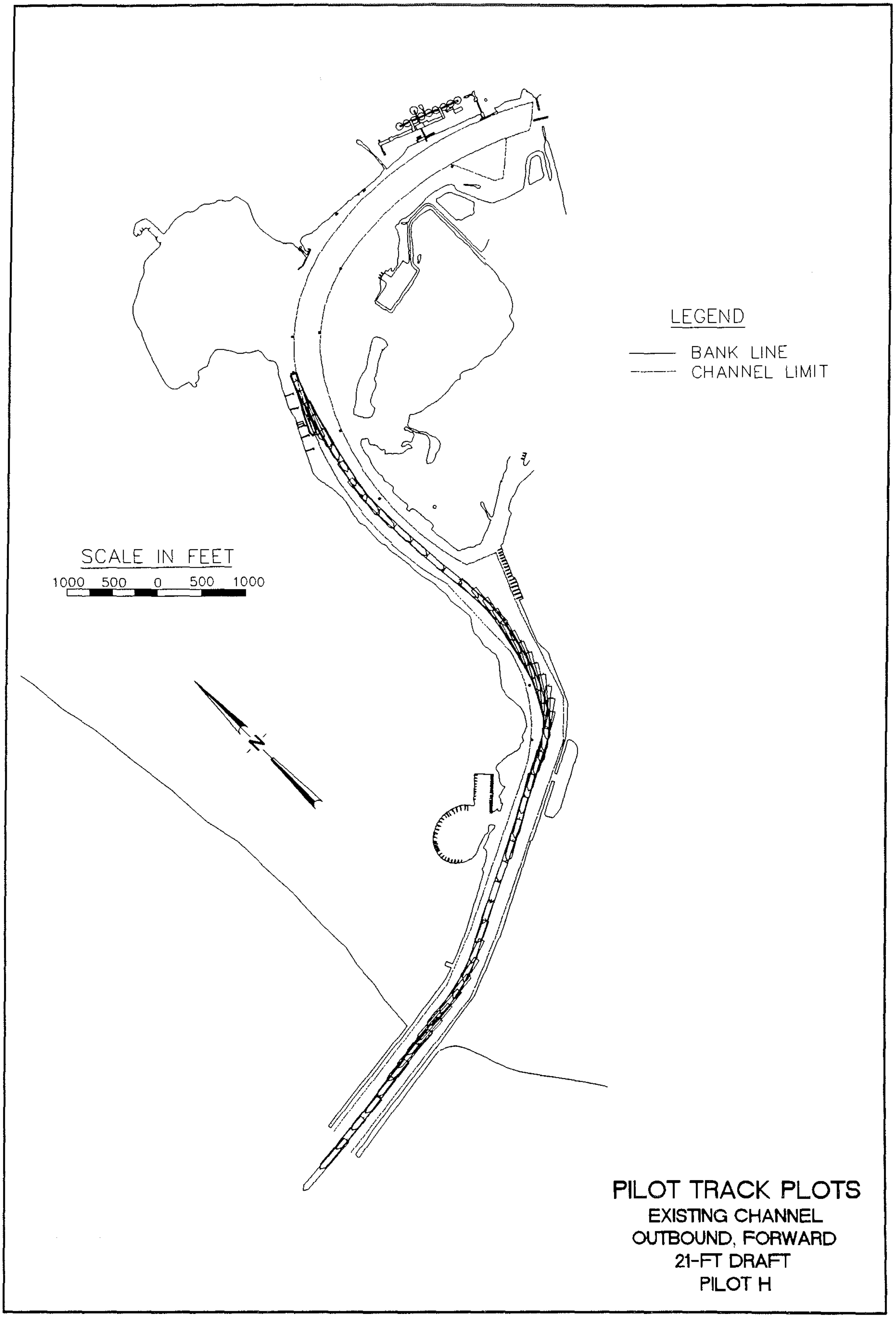

LEGEND
BANK LINE
CHANNEL LIMIT
SCALE IN FEET
1000 500 0 500 1000
N
PILOT TRACK PLOTS
PLAN B CHANNEL
INBOUND, BACKING
18.5-FT DRAFT
PILOT H

Plate 38



PILOT TRACK PLOTS
EXISTING CHANNEL
OUTBOUND, FORWARD
21-FT DRAFT
PILOT G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BANK LINE
CHANNEL LIMIT
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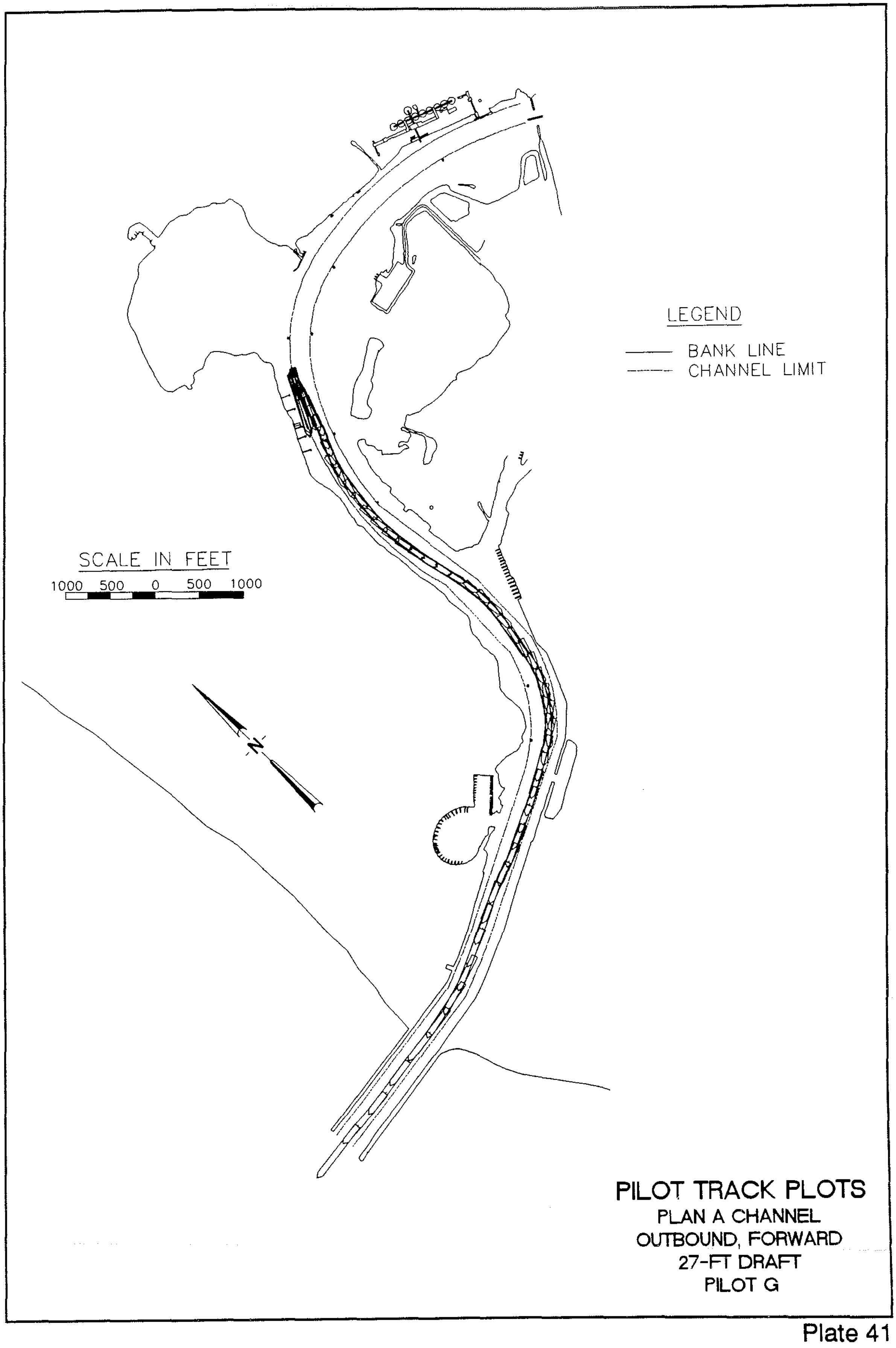
EXISTING CHANNEL
OUTBOUND, FORWARD
21-FT DRAFT
PILOT H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CHANNEL LIMIT
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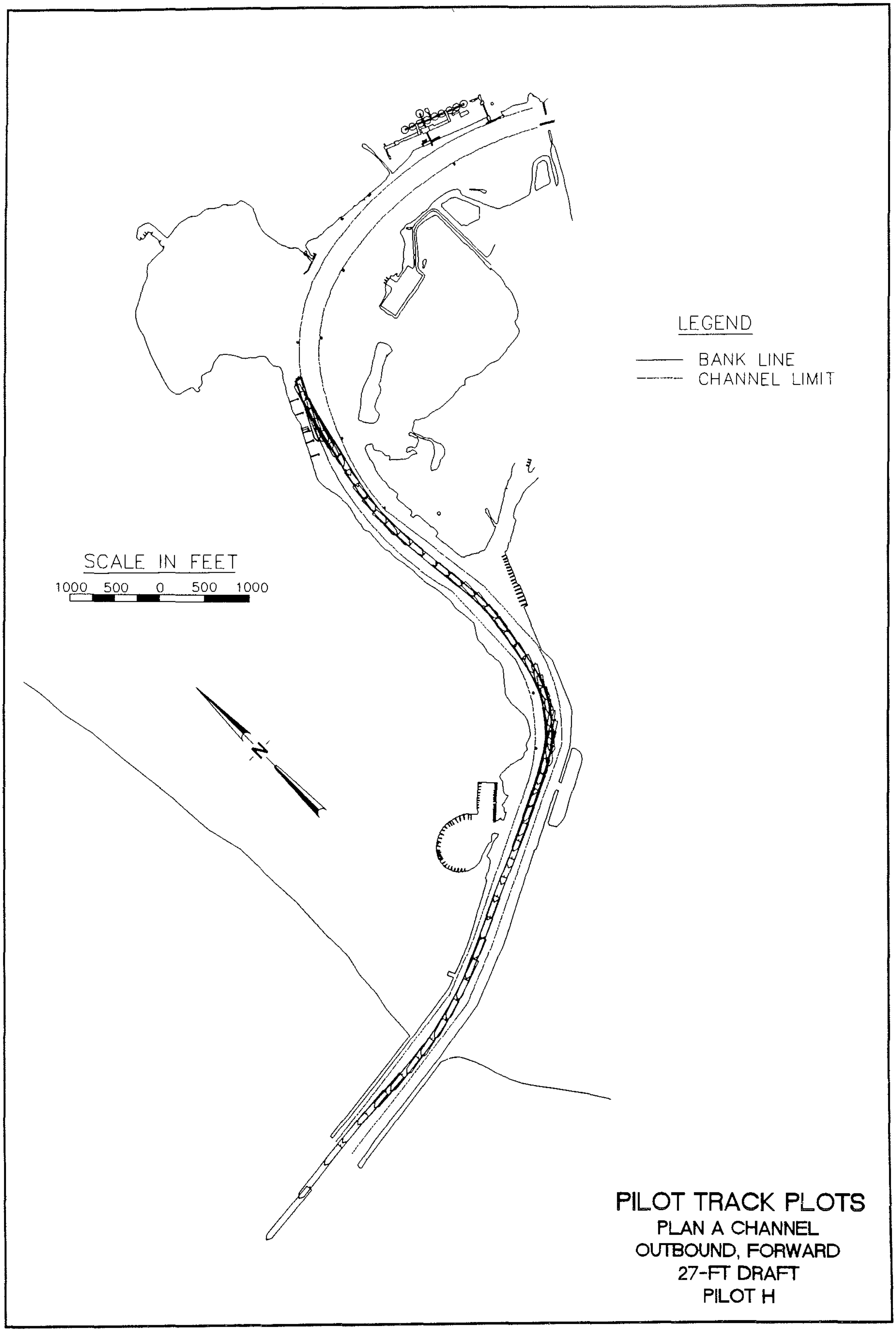
PLAN A CHANNEL
OUTBOUND, FORWARD
27-FT DRAFT
PILOT G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CHANNEL LIMIT
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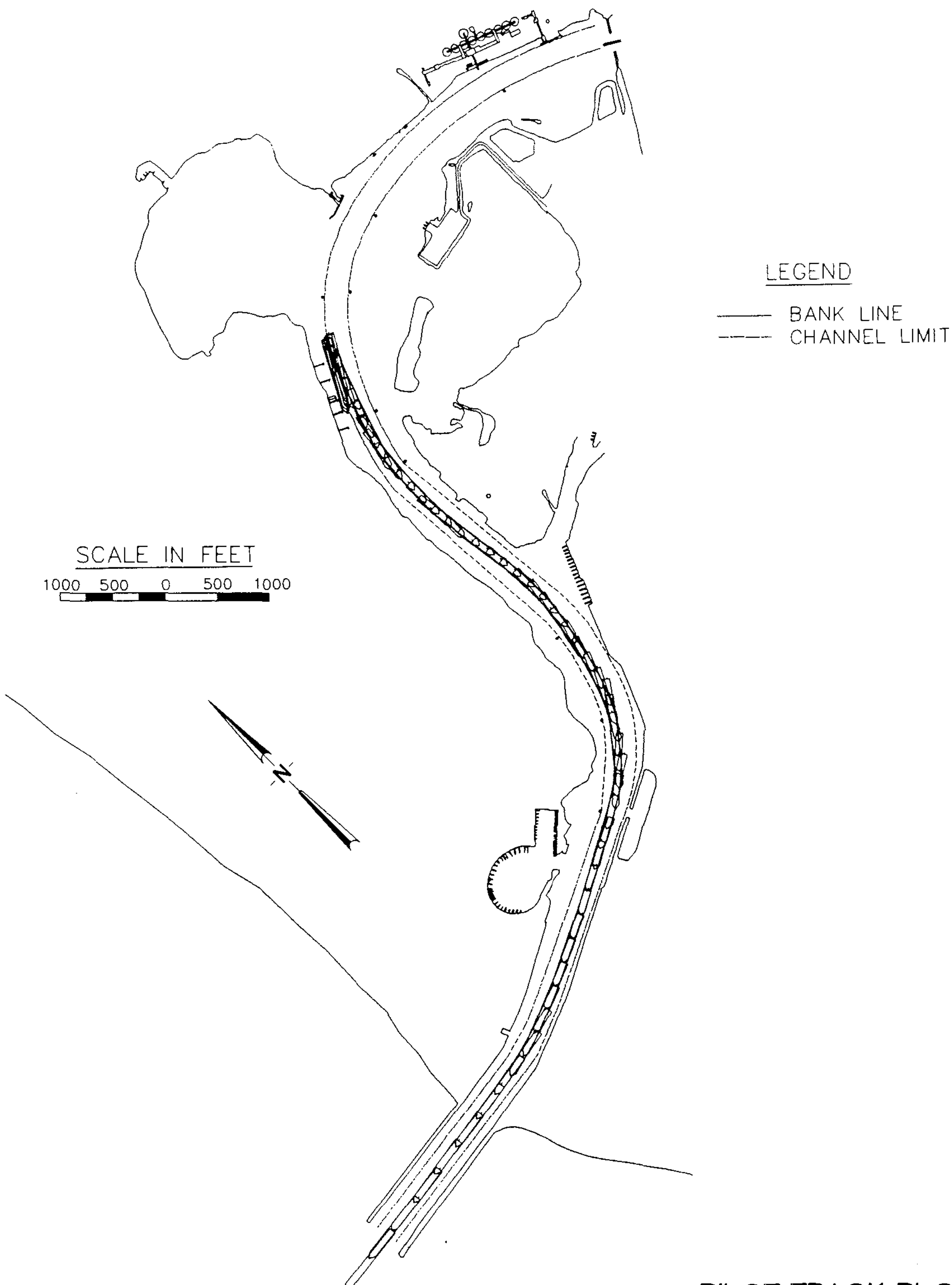
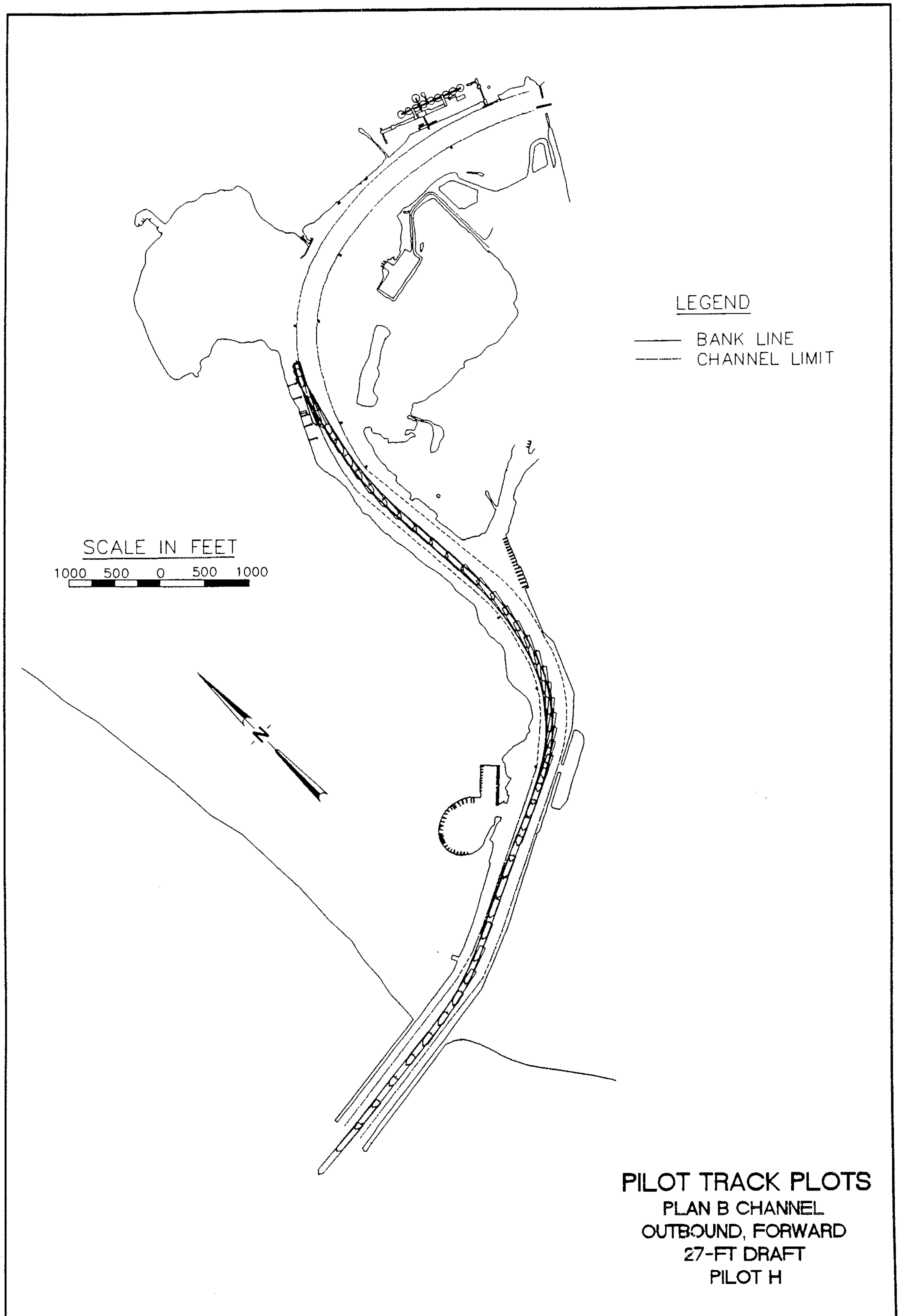
PILOT TRACK PLOTS
PLAN A CHANNEL
OUTBOUND, FORWARD
27-FT DRAFT
PILOT H

Plate 42



PILOT TRACK PLOTS
PLAN B CHANNEL
OUTBOUND, FORWARD
27-FT DRAFT
PILOT G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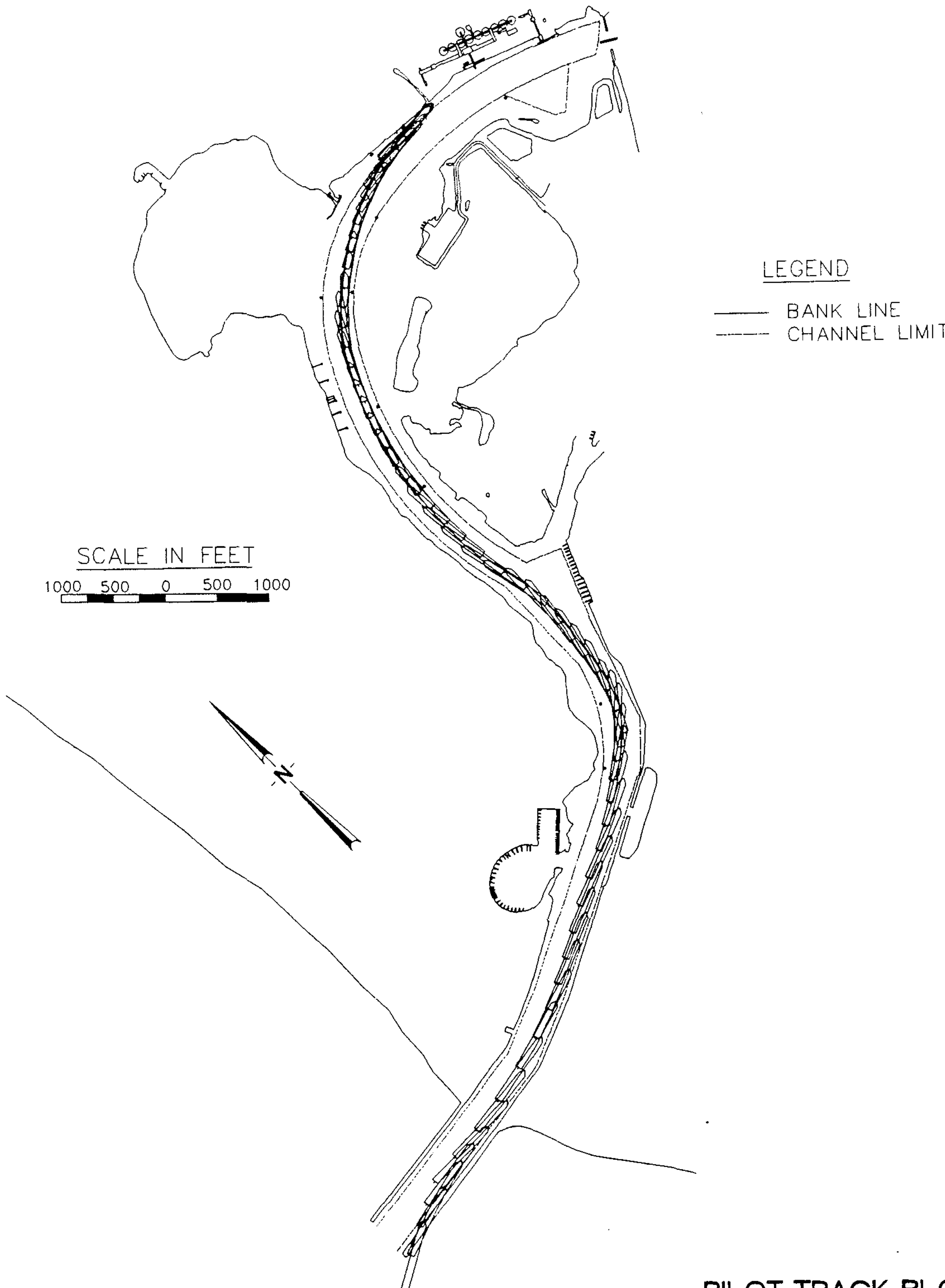
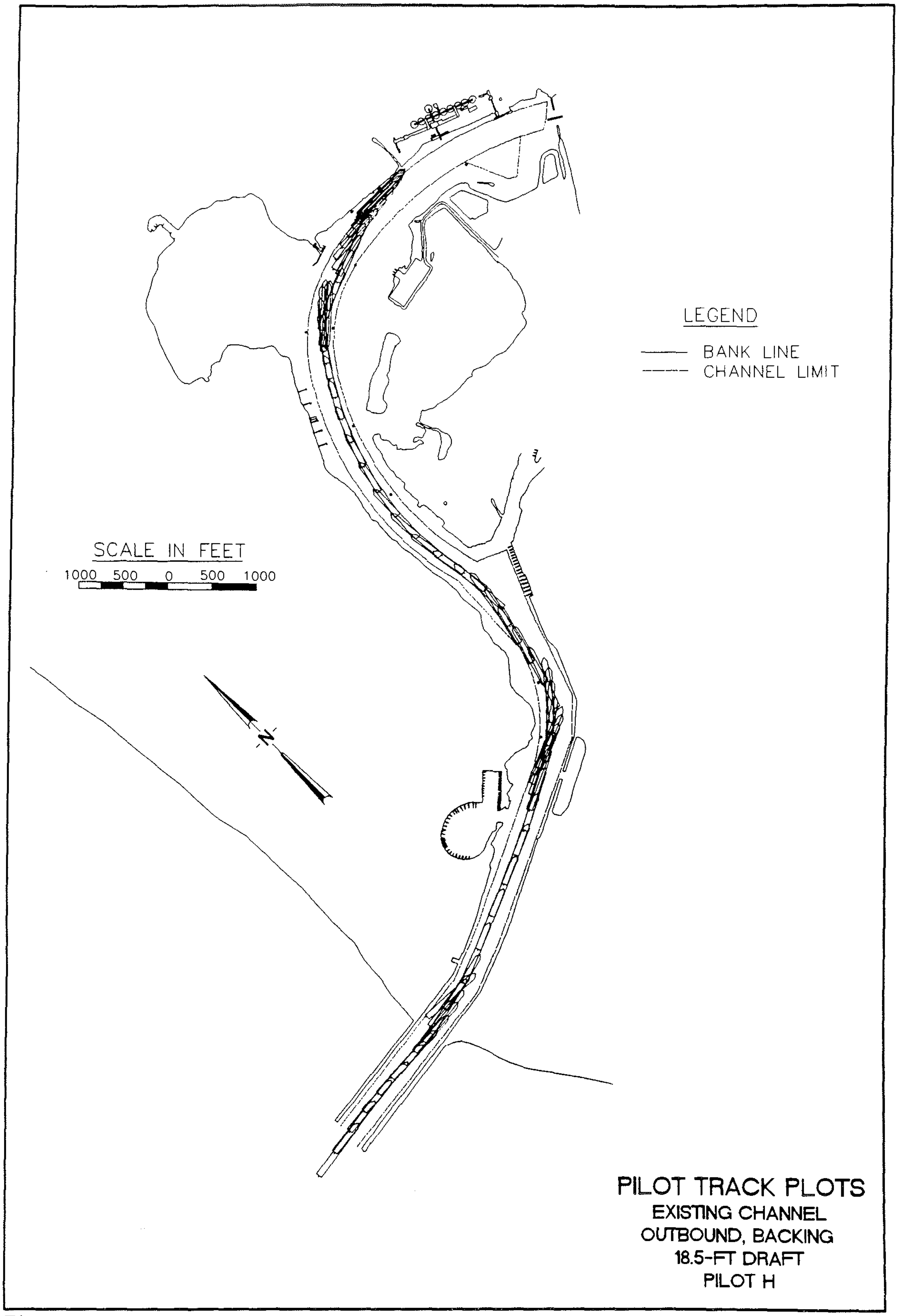
PLAN B CHANNEL
OUTBOUND, FORWARD
27-FT DRAFT
PILOT H



PILOT TRACK PLOTS
EXISTING CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT
PILOT G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CHANNEL LIMIT
SCALE IN FEET
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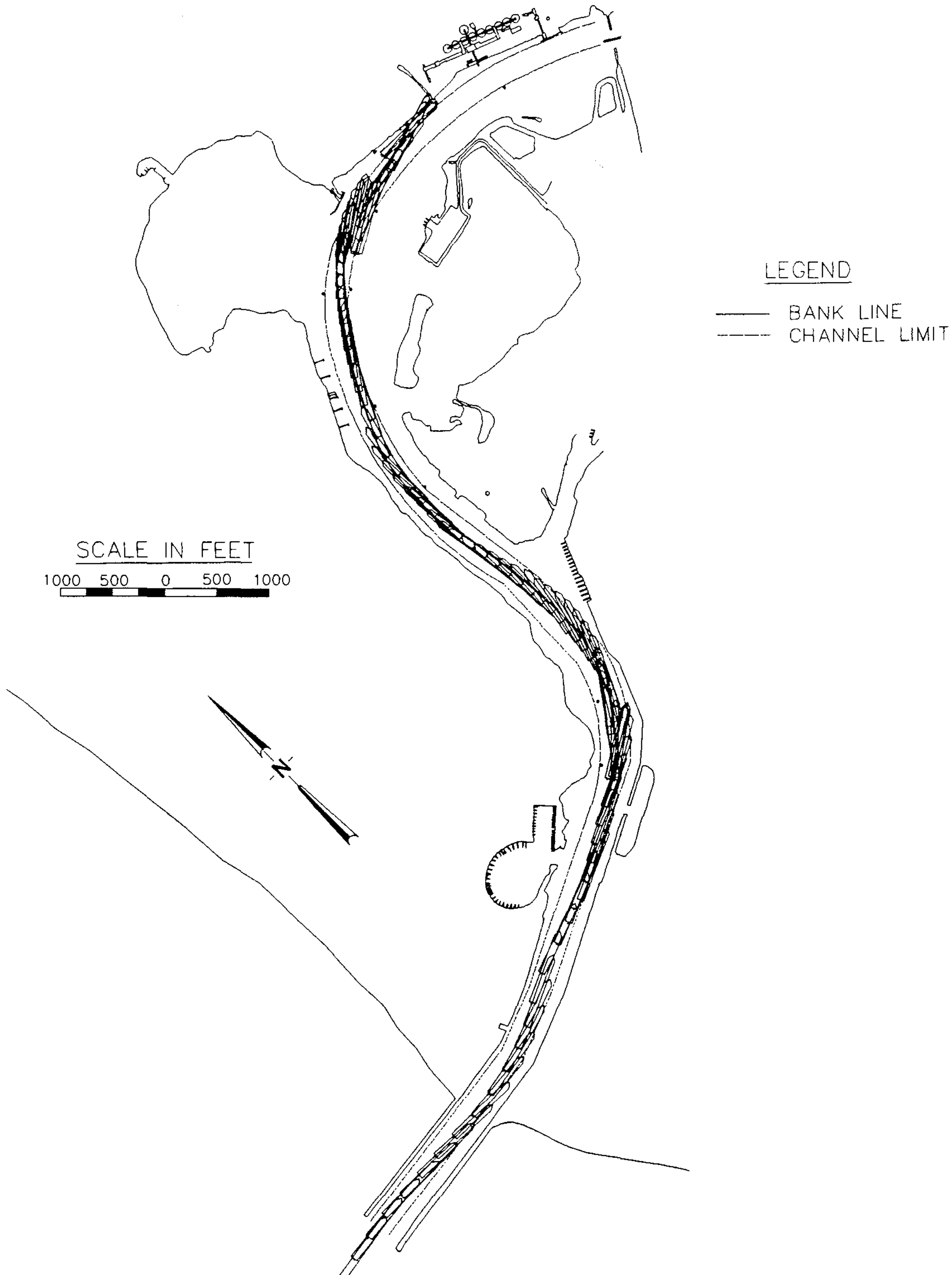
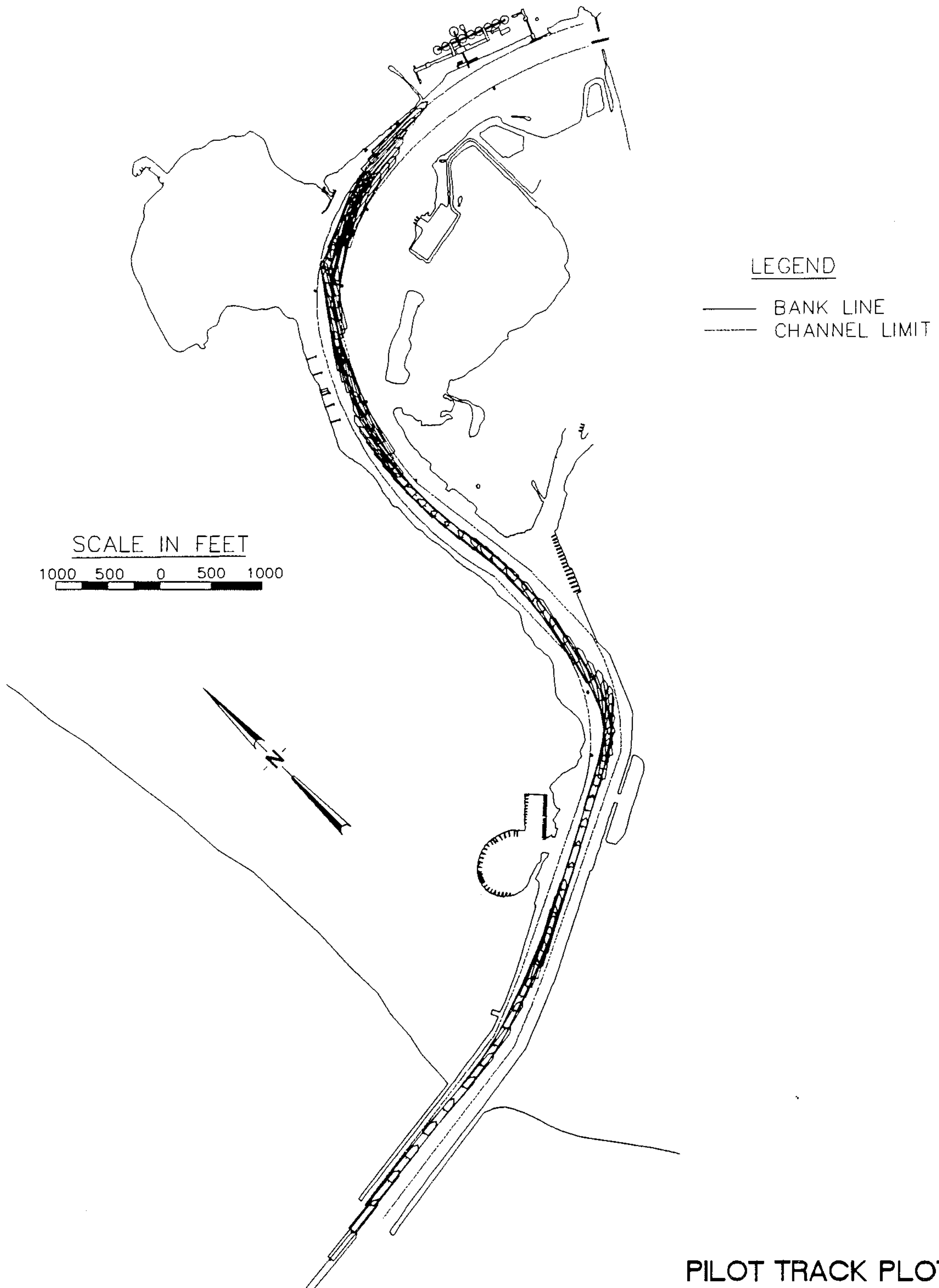
PILOT TRACK PLOTS
EXISTING CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT
PILOT H

Plate 46



PILOT TRACK PLOTS
PLAN A CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT
PILOT G



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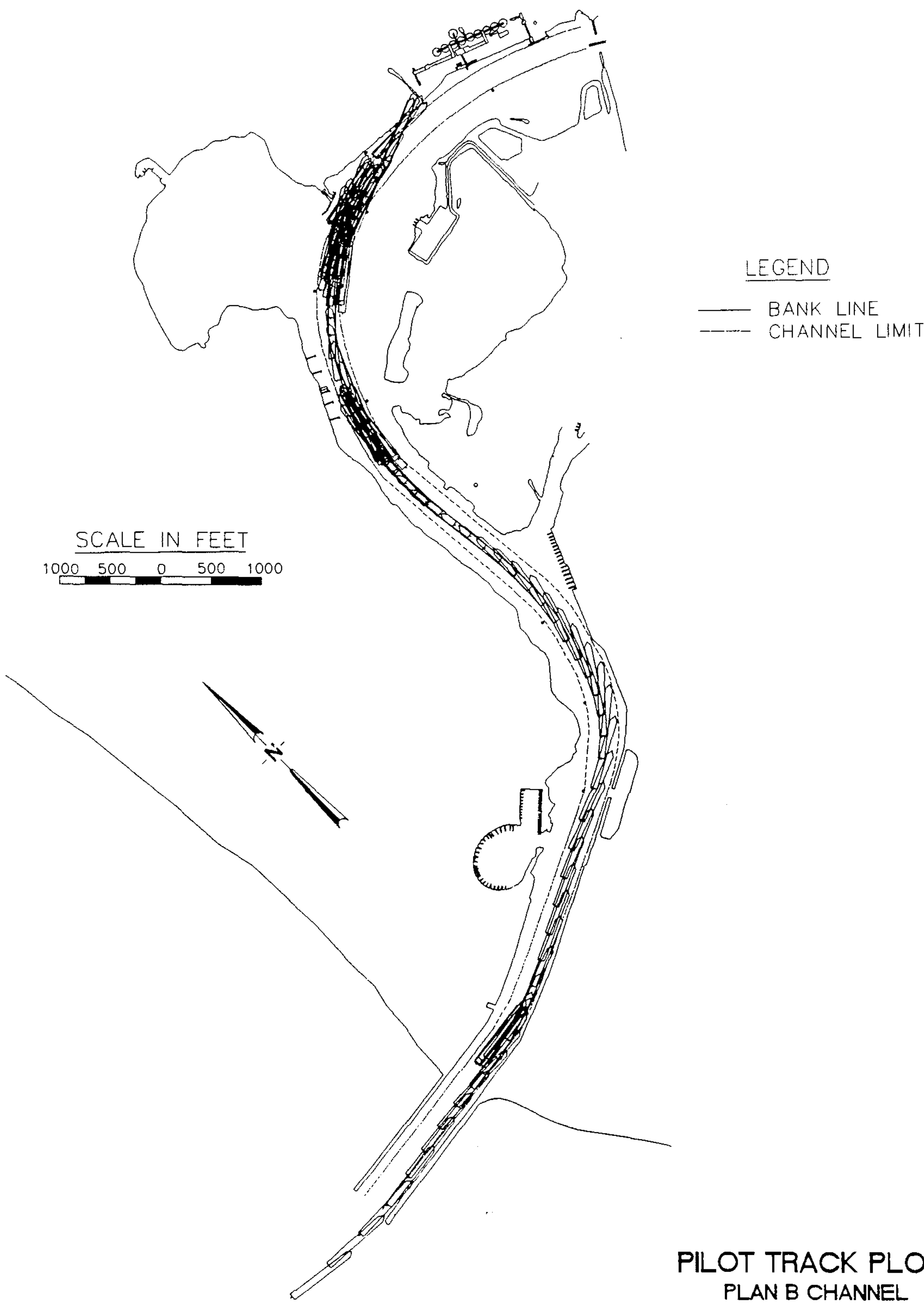
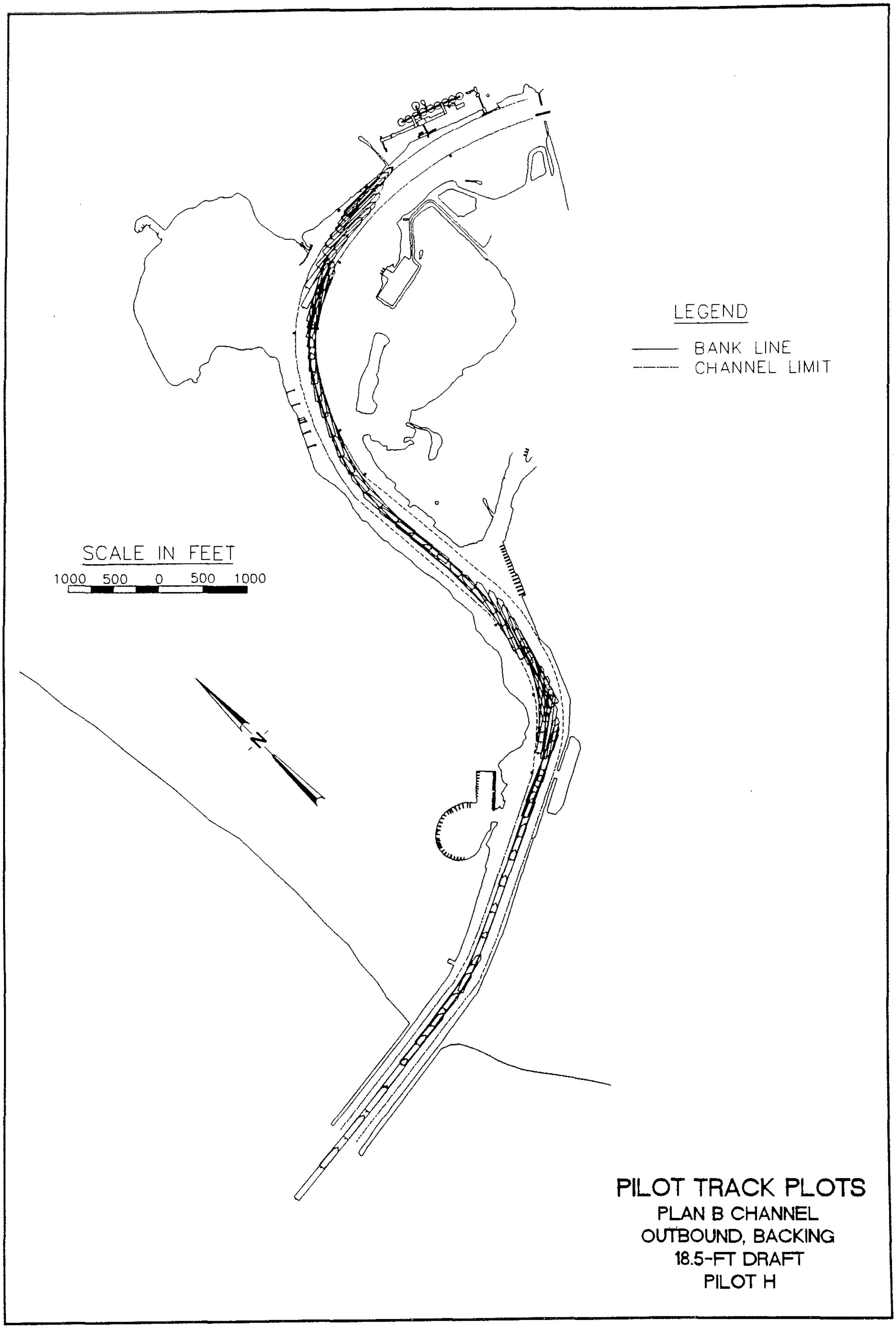
PLAN A CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT
PILOT H



PILOT TRACK PLOTS
PLAN B CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT
PILOT G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CHANNEL LIMIT
SCALE IN FEET
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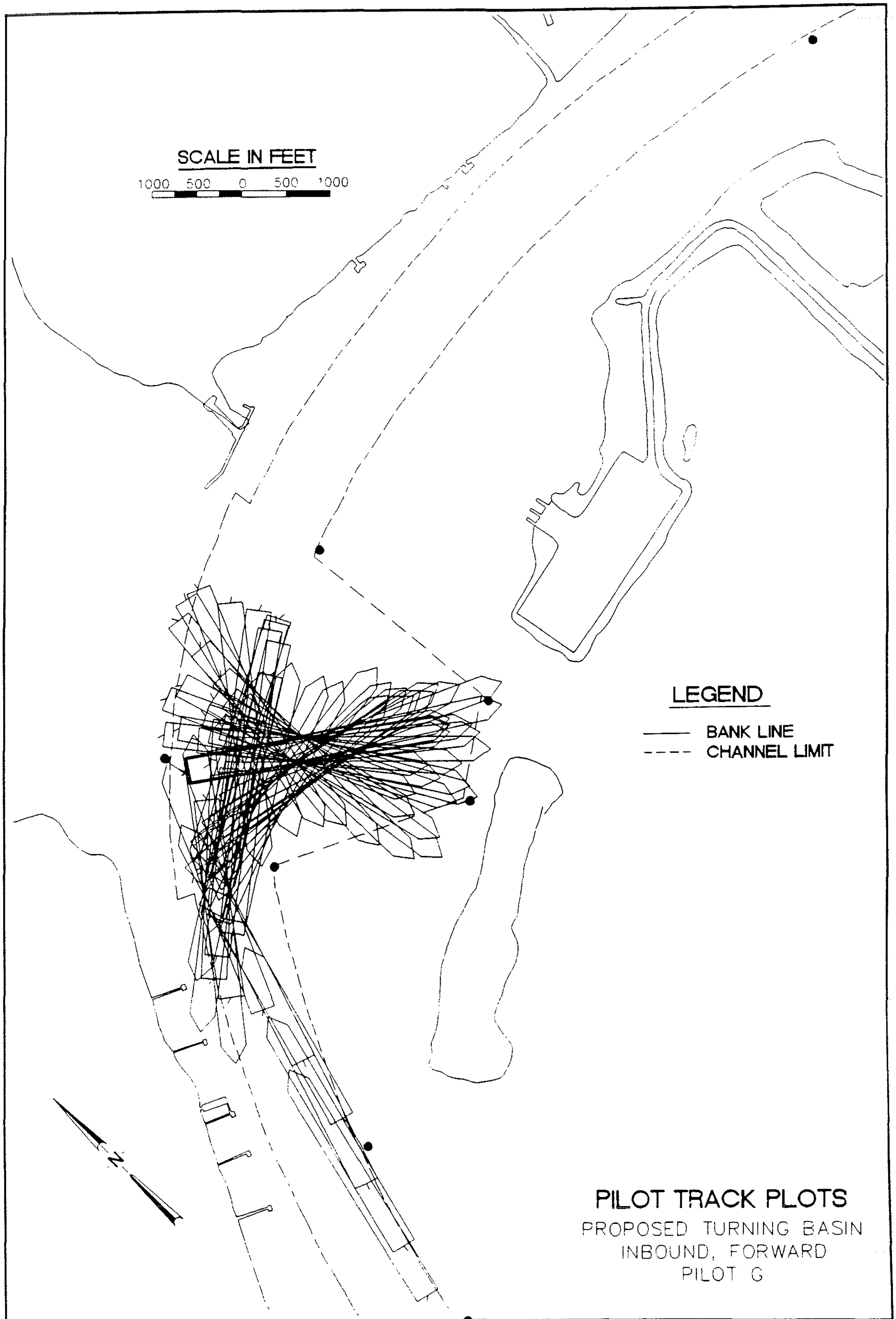
PILOT TRACK PLOTS
PLAN B CHANNEL
OUTBOUND, BACKING
18.5-FT DRAFT
PILOT H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LEGEND
BANK LINE
CHANNEL LIMIT
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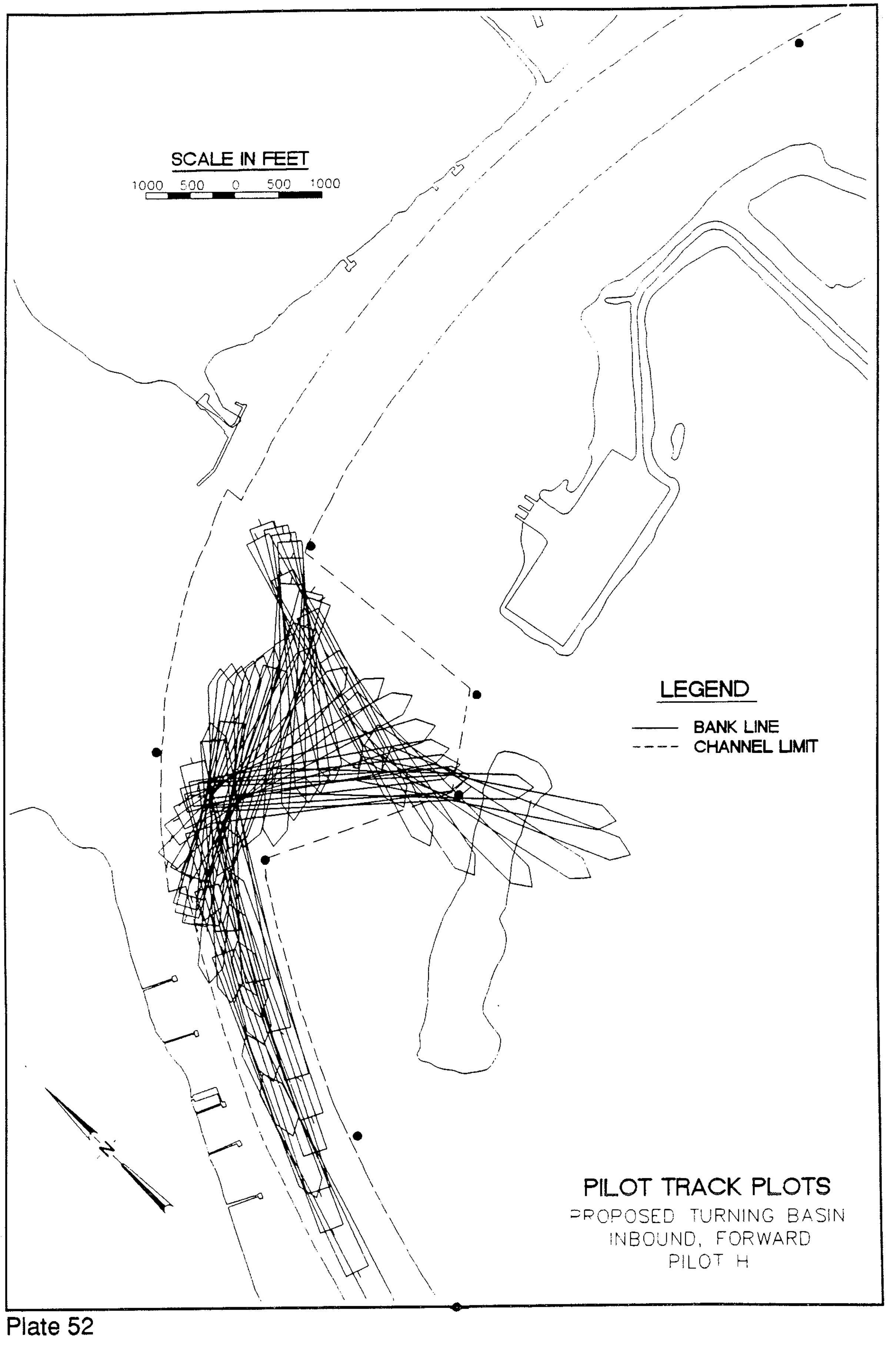
PILOT TRACK PLOTS
PROPOSED TURNING BASIN
INBOUND, FORWARD
PILOT G


SCALE IN FEET
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LEGEND
BANK LINE
CHANNEL LIMIT
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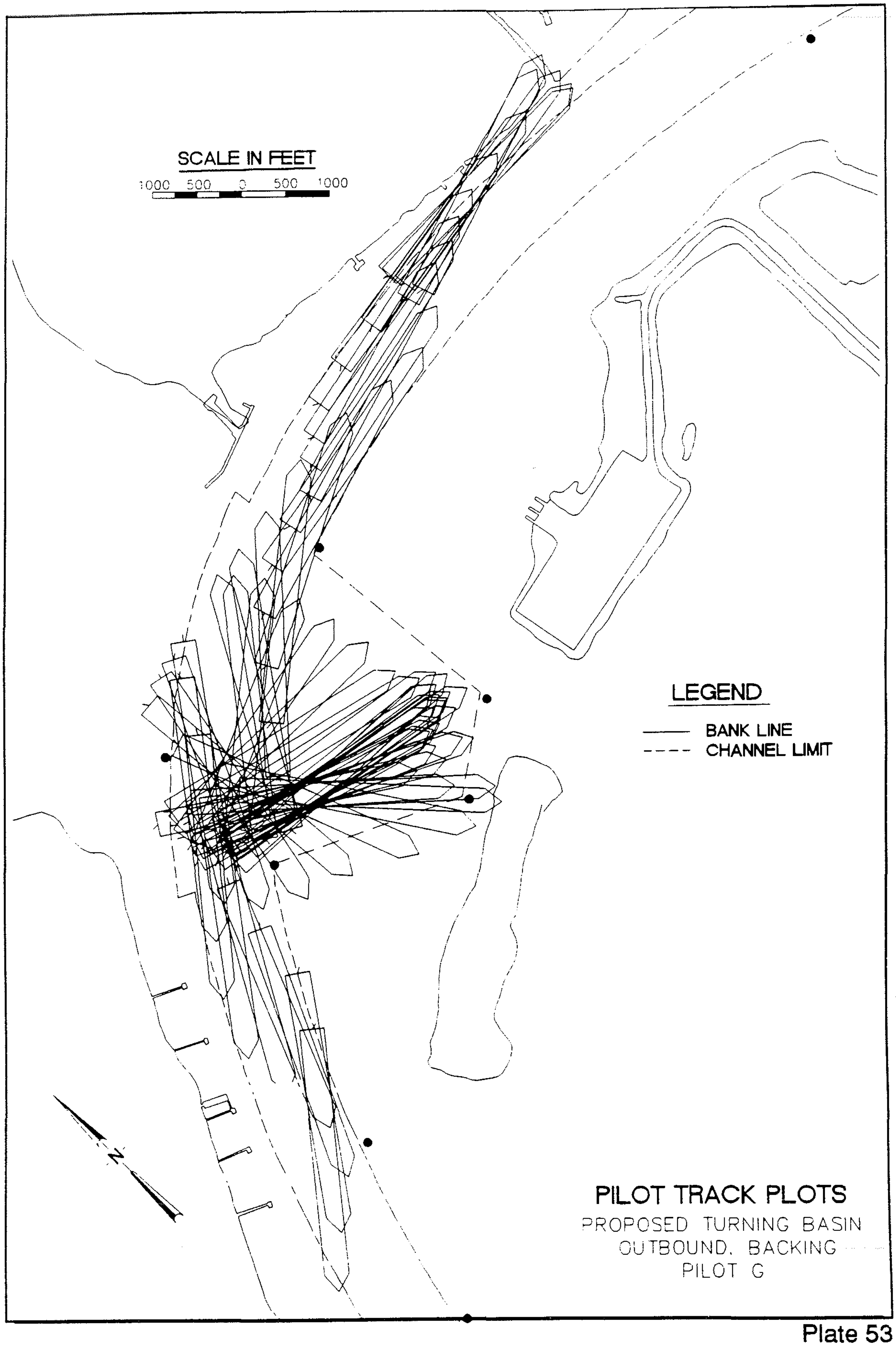
PILOT TRACK PLOTS
PROPOSED TURNING BASIN
INBOUND, FORWARD
PILOT H

Plate 52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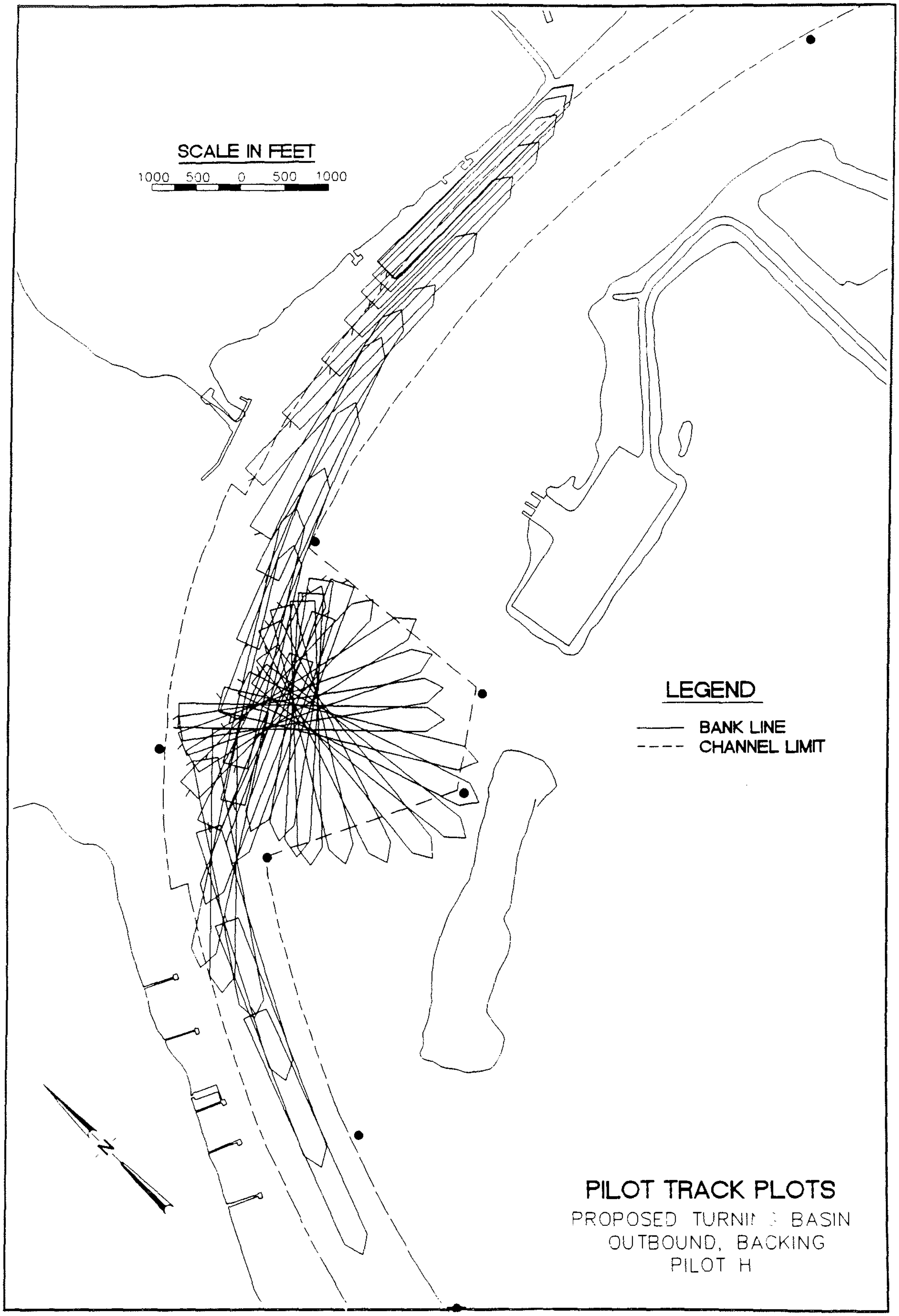
LEGEND
BANK LINE
CHANNEL LIMIT
N
PILOT TRACK PLOTS
PROPOSED TURNING BASIN
OUTBOUND, BACKING
PILOT G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LEGEND
BANK LINE
CHANNEL LIMIT
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PILOT TRACK PLOTS
PROPOSED TURNING BASIN
OUTBOUND, BACKING
PILOT H

Plate 54

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13. ABSTRACT *(Maximum 200 words)*

A real-time ship simulation investigation of the proposed designs for deepening and narrowing the navigation channel for Grand Haven Harbor, Michigan, was conducted. The purpose of the study was to determine if the navigation channel could be deepened from 21 to 27 ft and narrowed from the existing 300 ft to 225 ft and maintain adequate safety. A numerical model of the existing channel from Lake Michigan to the upper limit of the maintained channel was developed. The numerically generated currents were validated independently by two test pilots from the study area since no recorded current velocities exist. They independently reached the same conclusion that the currents should be approximately 1.1 mph. The pilots tested the existing 300-ft channel and two different 225-ft channel proposals. Testing was performed on the U.S. Army Engineer Waterways Experiment Station ship simulator.

These tests demonstrated that either of the 225-ft channel proposals would be acceptable at a 27-ft depth, the channel through the jetties should be centered between the jetties, and range markers should be provided.

14. SUBJECT TERMS

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Channel design	Ship	
Grand Haven Harbor	Simulation	

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