APPENDIX C

Ship Simulator Applications to Waterways Design — Lessons Learned

C-1. Introduction. The ERDC/WES Ship and Tow Simulator has been used to study over 30 navigation channel projects since 1983. Most of these studies have involved design issues of required channel geometry and alignment for adequate ship safety and maneuverability. Simulator results and recommendations have been well received by the professional pilots and the design engineers of the U.S. Army Corps of Engineers Districts.

We present an overview of the ERDC/WES Simulator and the study methodology. Selected simulation application test results are reviewed, and some generalized design guidance is presented. A research effort to address some of the simulator limitations is outlined.

The use of computer simulation modeling of ship and tow maneuvering was started at ERDC/WES in the 1970's (Ankeny et al. 1978, Huval and Pickering 1978). Physical scale models had been in routine use for assessment of navigation, however, for a number of years (Franco and McKellar 1966). The availability of the WES Simulator for use in waterway and port design was announced in 1983 (ETL 1110-2-289, 1983). The simulator is used for both ship and pushtow (towboats and barge flotillas) studies, sometimes both on the same project, as required.

C-2. Simulator Description. The ERDC/WES Simulator includes models of a ship or tow, the navigation channel, the currents, the wind, the visual scene, the radar image, tugs and thrusters, the ship or towboat bridge controls, and typical bridge instruments. The simulator can be used with human piloted control in real-time (Figure C-1) or an autopilot, which follows a track-keeping function for fast-time tests. The autopilot has a "look-ahead" capability to anticipate a channel turn. The ship model is complete with hull dynamics; engine thrust; control surfaces; cross-term interactions; bottom effects; bank effects; current effects; wind effects; ship/ship interactions; and tug, bow, and stern thruster forces. The simulator system is shown in Figure C-2.

The visual and radar models depict the changing scene in enough detail to enable the pilot to determine his location and the rate of motion. These details include formal navigation aids and realistic cultural features often used to pilot ships. The channel model produces the effects on the ship that will cause the ship to respond to the channel similar to the way it does in real life using a detailed description of the currents, channel banks, and underkeel clearance throughout the channel. These factors are the outside perturbations that act on the ship and are crucial to realistic channel design studies.

The pilot, as seen in Figure C-3, has full access to visual cues and instrumentation information and controls normally available to him on board the real ship. The use of professional pilots from the area being simulated may be the most important factor and a primary reason for conducting a simulation study. Simulations are used to bring the skills and judgment of the pilot into the waterway design process and to determine the limits of the ship maneuvering characteristics in the specific navigation channel environment. Simulation studies are normally conducted as comparative studies in which one alternative channel design can be compared against a base (usually existing) condition or another design.

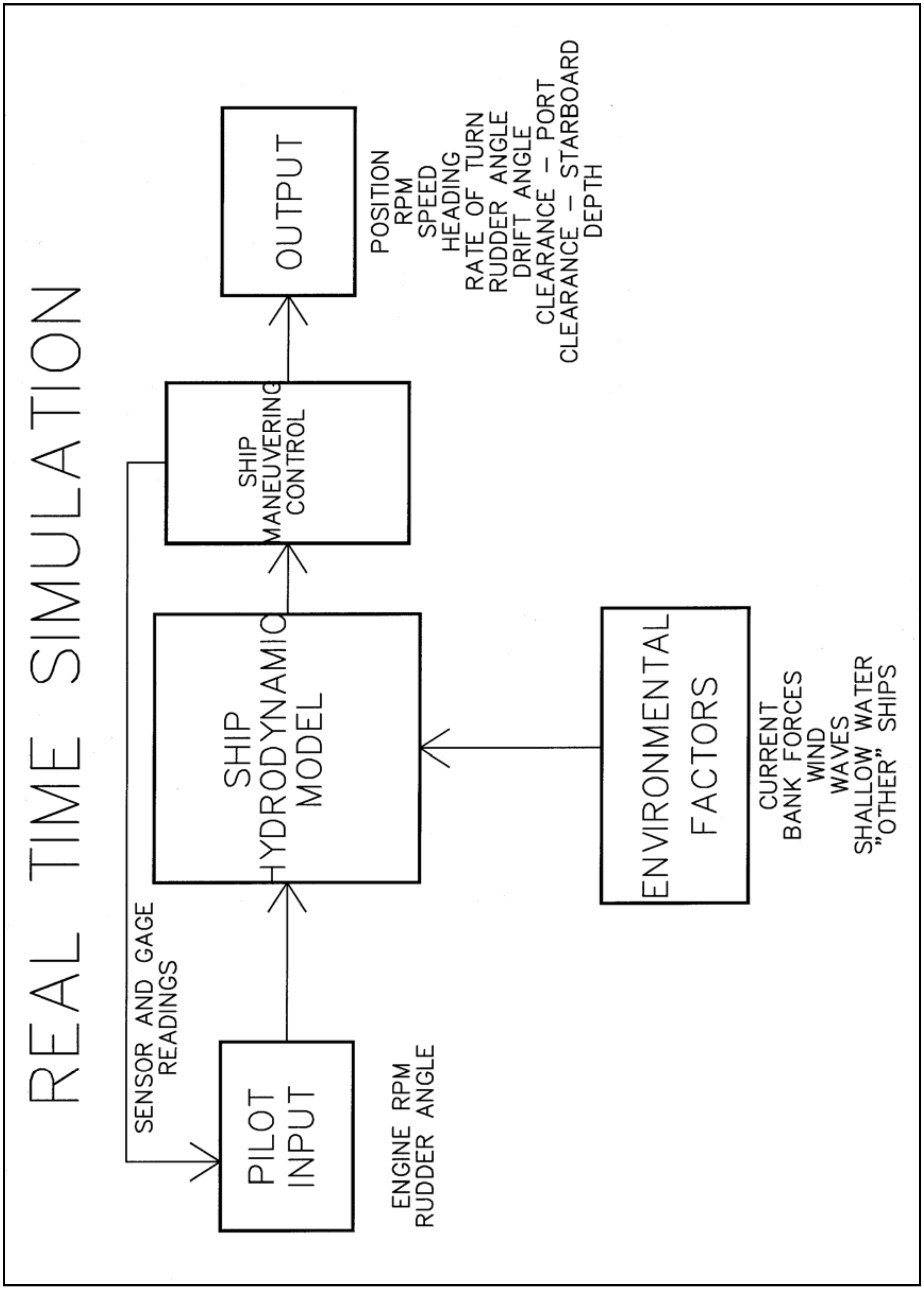

Figure C-1. Real-time simulation

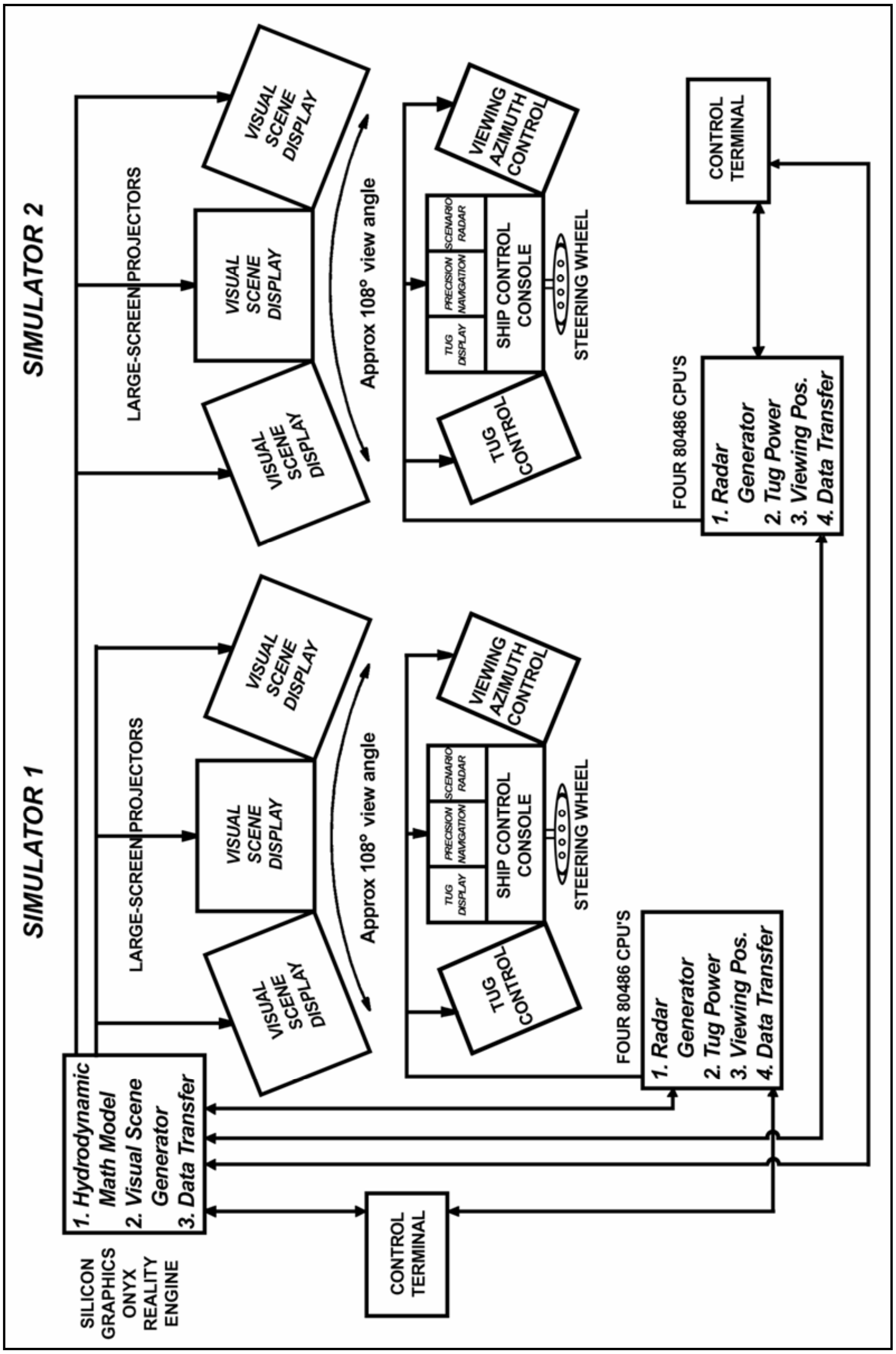

Figure C-2. ERDC ship simulator system

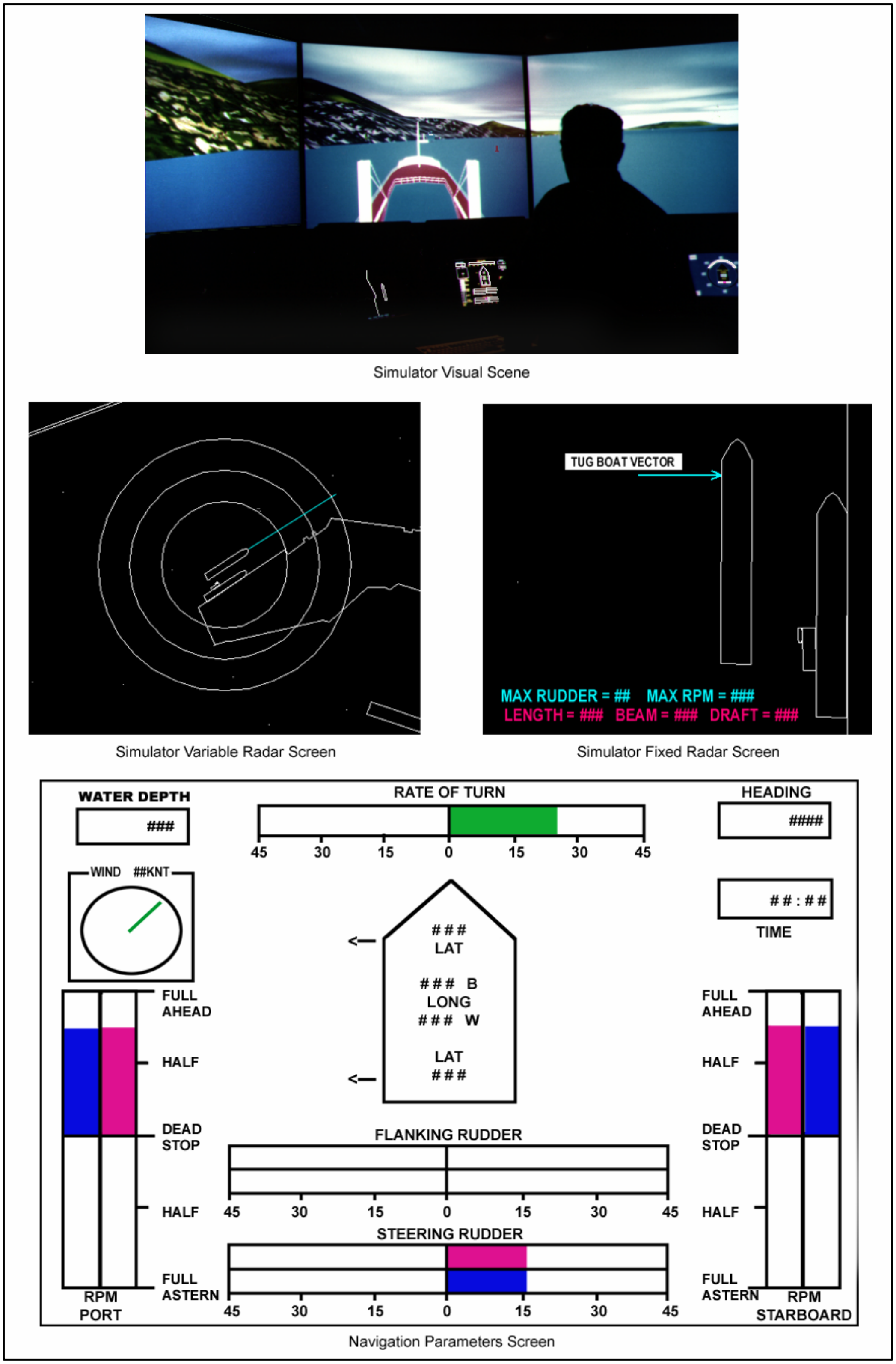

Figure C-3. Ship/tow Simulator visual scene and instrumentation

C-3. Study Methodology. Simulation studies can be used during different phases of waterway or port improvement projects. The earlier the simulation is introduced during project development, the more influence it can have on optimizing the design. At the reconnaissance level, a simulation study can identify the truly superior alternatives, eliminate the poor ones, and identify the required maneuvering areas. The same is true in the feasibility stage but with more detail. When the design has basically been set, a simulation study can refine and optimize the channel dimensions and alignment features and establish operational procedures. A simulation study “localizes” the navigation requirements; the local conditions are used to develop a final design. If operational problems exist or new operations are being considered, the simulation model can define the level of improvement and safety of the alternative designs.

Definition of the problem to be studied is important and must include a full understanding of the important issues and all of the ramifications, especially the range of ship operations and limitations, local pilotage, and environmental conditions. Navigation conditions for simulator testing have to be selected with care. Normally, reasonably high levels of wind and current conditions are used.

The modeling of the river or tidal currents is expensive and time-consuming; but it is an extremely critical part of most studies. Finite element mathematical modeling of the currents provides the most accurate and flexible modeling in many cases. There have been, unfortunately, several examples in the past of current modeling on a grid spacing that was larger than the channel width. How can current patterns at channel turns be resolved on such a grid? At least five or more grid points are included over the width of the channel in the ERDC/WES Simulator.

It is also important that the currents be accurately modeled in the simulator. Some simulator models are limited in the ability to represent the spatial distribution of currents. Accurate definition of current patterns across and along the channel is required for adequate simulation. The ERDC/WES Simulator allows eight depth and velocity stations over the channel width and interpolates between definition points along and across the channel.

C-4. Applications.

a. J. F. Baldwin II Long Wharf.

(1) Study description. One of the first studies (Huval et al. 1985) conducted resulted in major savings of construction costs and reduced dredging quantities requiring disposal. This study involved deepening a channel from deepwater in San Francisco Bay to the Richmond Long Wharf facility, a major oil terminal on the west coast of the United States (Figure C-4). The project improvement called for deepening from 35 to 45 ft to allow 150,000 deadweight tons (dwt) tankers to go directly to the terminal rather than to lighter, smaller tankers in the bay, always risking an oil spill. Questions were raised about the safety of the larger tanker approaching the terminal in the maneuvering area and the approach channel width required. Maneuvers depend on the phase of the tide, flood, or ebb, when the docking occurs; pilots approach the dock while stemming the tide. Tidal current data were developed from special measurements on the San Francisco Bay scale model.

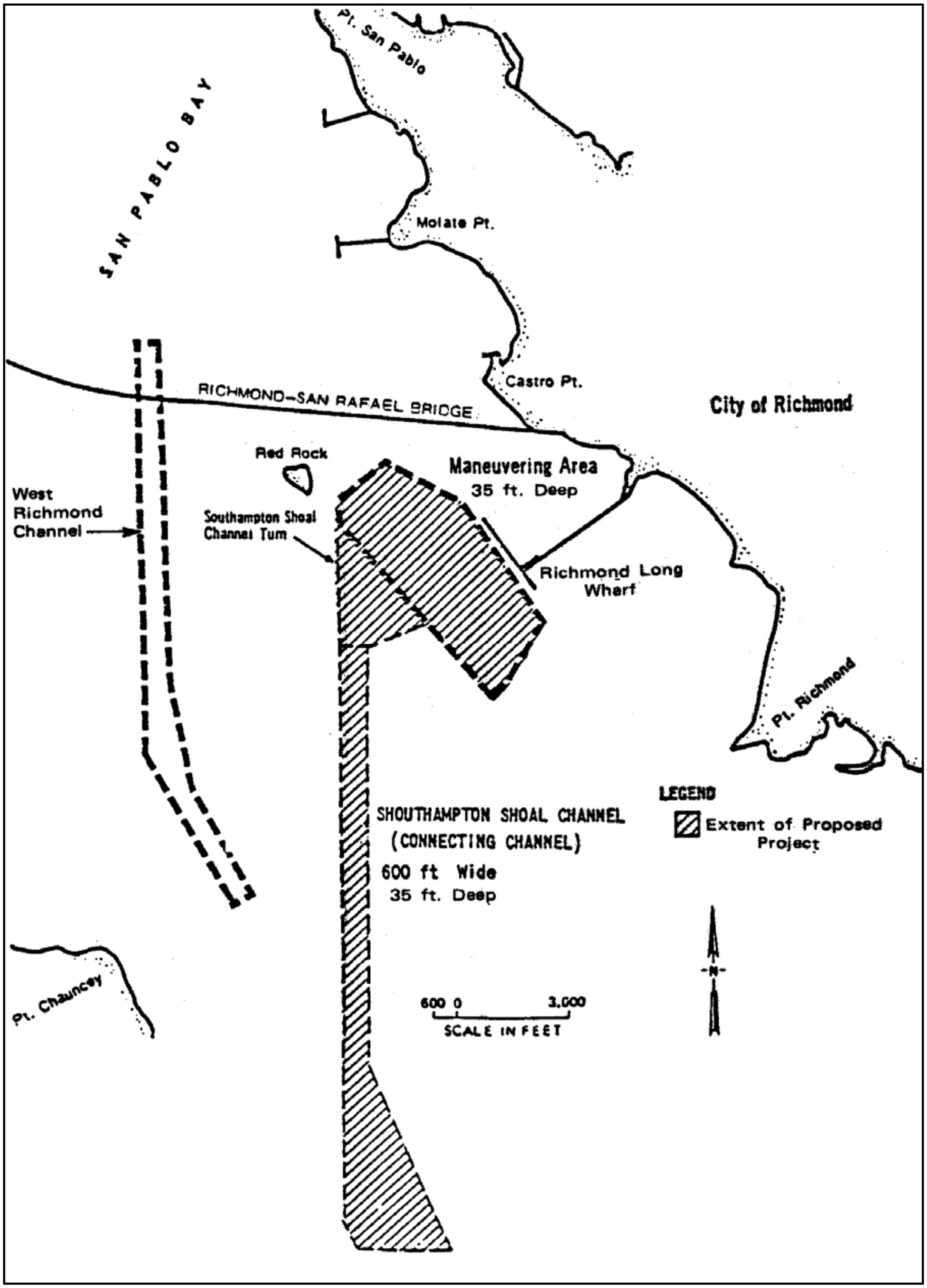

Figure C-4. Connecting channel from San Francisco Bay to Richmond Long Wharf facility

Project construction was imminent. Early tests in the WES Simulator indicated that the proposed 600-ft approach channel width was required because of strong crosscurrent and reduced ship forward speed. Docking approach maneuvers did not take as much room as expected. As a result of a reanalysis of test results and a second set of simulations, the area of the maneuvering area was reduced significantly, resulting in a savings of $1.8 million and 1.43 million cu yd of dredging. The project cost is estimated to be $12.8 million and the simulator study cost was $110,000.

(2) Lessons learned. The simulator model was a very good representation of the real world. Engineers can get a good feel for the navigation problems from simulation tests and develop adjustments in the design. Local pilots are very important to a successful study, which must include their skills, experience, local knowledge, special operations, cooperation, and coordination. Simulation provides a means to develop or enhance a consensus on the design between the planners, project managers, engineers, pilots, port authorities, and terminal operators. Optimizing a design can help reduce environmental impacts and project opposition and environmental mitigation costs. It is never too late to adjust the design; even after construction, the project can be corrected if a navigation or maintenance dredging problem exists.

b. Grays Harbor.

(1) Study description. Grays Harbor (Figure C-5) is another example that demonstrated the benefits of simulation studies (Hewlett et al. 1991). This project consists of two portions, the outer harbor in open bay water and the inner harbor or river portion. The project involved deepening and widening the navigation channel to allow timber ships that are presently calling to be loaded to a greater draft and thus operate more efficiently. The channels were to be deepened from 30 to 38 ft and the outer channel widened from 350 ft to 400 ft throughout. Pilots were brought in from the local area early in the study and the District sponsor was actively involved. Physical scale model data from a previous study were used but the model was not available to allow special data collection as in the previous case. It was found that the pilots routinely took the ships beyond the limits of the existing authorized as well as the proposed, deepened channels into naturally deep areas. However, they reported that the existing 350-ft-wide channel deepened to 38 ft provided more control than the widened channel, as a result of higher bank forces. They preferred the narrower channel; however, there had to be some adjustments at the channel turns to allow for the wide swing of the ship and the transition from locally widened areas to the confined 350-ft channel (Figure C-6). Savings in dredging volume, environmental impact (impact on crabs), and project costs were $2 million.

The interior portion involved ship maneuvering in a river environment, with one large bend and a narrow channel with high banks. Here the point current measurements from the scale model became limited and not always available where data were needed. Bank effects on the maneuvering ships became significant. A narrow railroad bridge span (125 ft) was to be increased to 185 ft by bridge replacement and redesigning the timber fendering on another nearby highway bridge. Could larger ships than the current limit of 80-ft-beam, 30,000-dwt timber ships call the terminal at the head of the channel for greater benefits? With adjustments to the channel design upstream of the highway bridge, the simulations showed that with ships up to

100-ft-beam, 50,000 dwt, could safely transit through the modified bridges. The benefits from the nearly doubled cargo greatly outweighed project costs.

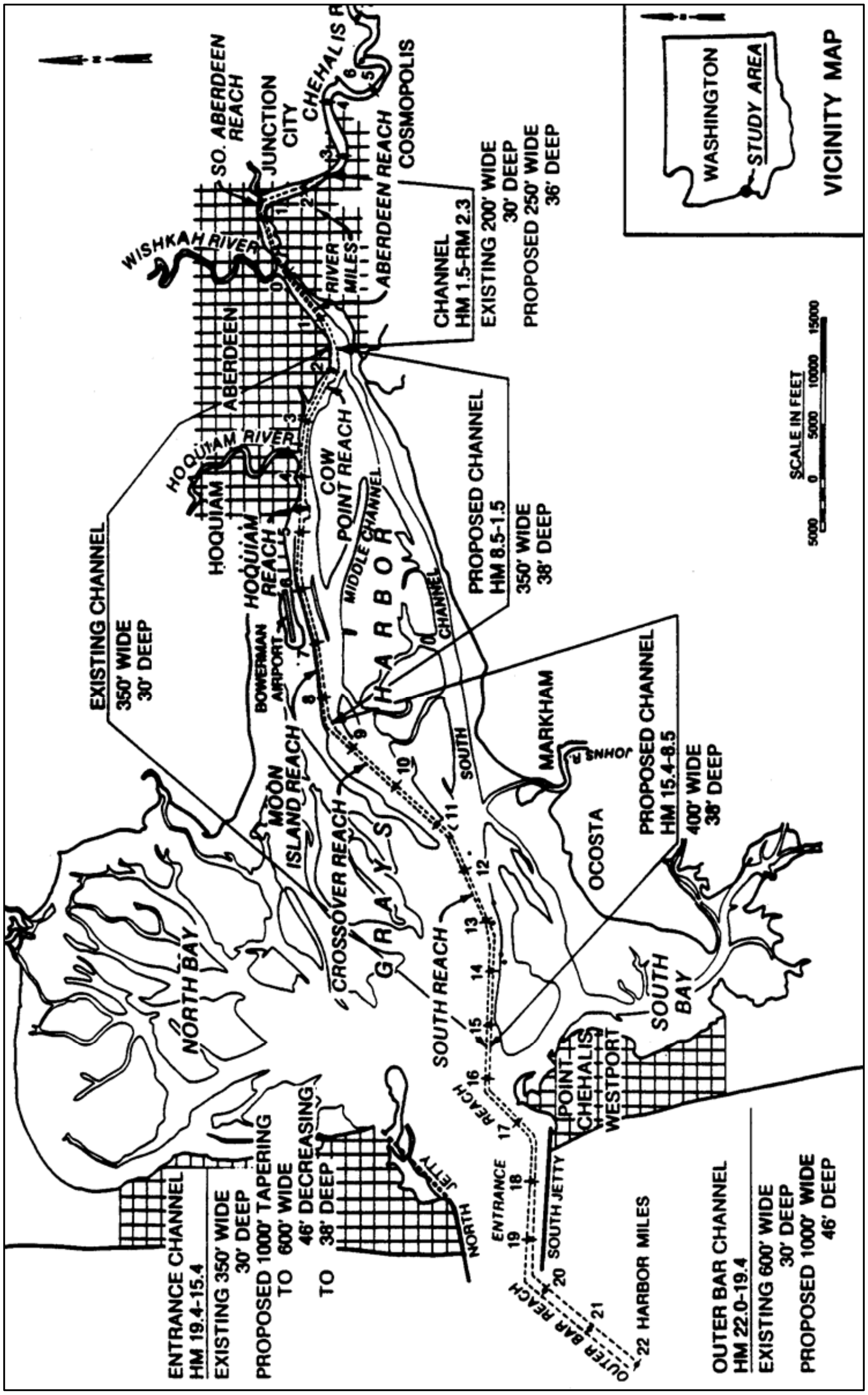

Figure C-5. Grays Harbor

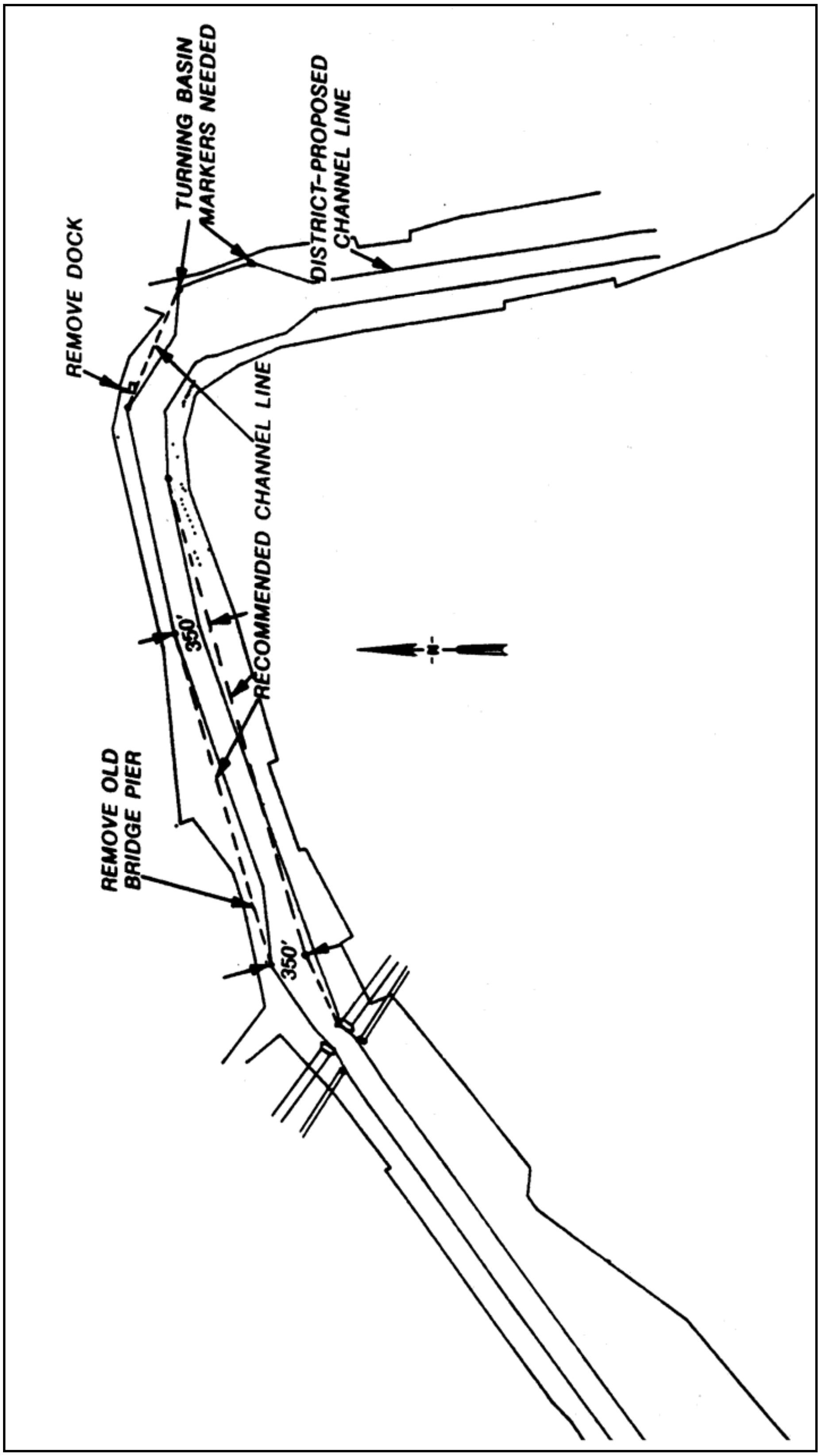

Figure C-6. Grays Harbor, recommended channel alignment

(2) Lessons Learned. Major project savings can be obtained by applying the simulator. The pilots suggested improvements; project engineers and managers were deeply involved and provided valuable feedback and interaction. The simulation study identified a potential problem for inbound transits not recognized by the engineers that required additional local channel widening. Point measurements from physical scale models do not provide adequate current pattern data needed for accurate simulations. Testing alternative channel design widths can identify improvements in navigation conditions, sometimes indicating that increased width is not always beneficial. The simulation study allowed the identification of additional project benefits for the proposed project.

c. *Bridge Relocation Study*.

(1) Study Description. A ship simulation study was conducted to determine the appropriate span increase for the Gilmerton Bridges in Portsmouth, VA. Docking pilots from the project site traveled to Vicksburg to maneuver the simulated vessels through several proposed fender layouts. The existing span width was 125 ft. The simulations revealed that a minimum of 150 ft was required and that the widening should be on the west side only. The design was approved by the pilots and the Norfolk District engineers.

(2) Lessons Learned. Vessel simulations can be used to evaluate proposed bridge span locations and width. Simulation of several span widths will assist in selection of the safest and most economically attractive alternative. Also, possible changes to the navigation channel and channel markings can be examined.

d. *Project Site Screening*.

(1) Study description. Simulation can be used in the early phases of navigation projects to include and define navigation requirements, even at the reconnaissance study level. A recent towboat simulation study of 13 potential navigation lock sites resulted in 22 different specific design alternatives on an inland waterway. Because of the many sites and flow combinations, a simplified river current model was used. The study allowed the ranking of the alternative design combinations based on piloted navigation qualities in a way never before possible. In the past, lock site navigability was considered in the design based on engineering judgment as to suitability. Real estate and foundation considerations usually governed lock site location, rather than the project purpose of navigation and its related factors, hydraulics, and channel alignment. From this study, it was clear that some sites were much better navigationally than others; the 22 alternatives were easily ranked into three categories: 6 were recommended, 5 were feasible, and 11 were unacceptable.

(2) Lessons learned. While river currents are important for towboat simulation, it is possible in some cases to develop an adequate current pattern without modeling in detail, particularly where the channel configuration will dominate navigation considerations. Navigation can and should be considered with the simulator early in the project so that major navigation hazards resulting from a poor choice of lock location can be avoided.

e. Port Jersey Channel.

(1) Study description. Not all simulator studies result in project savings from the originally planned design. The Port Jersey channel project (Figure C-7) called for deepening from the present 35 ft to the proposed 41 ft to allow fully loaded, 106-ft-beam, 950-ft-long containerships to call at the port. Several channel widths were being considered, including one 350-ft-wide plan, which would considerably reduce the present available width. The entrance into the design channel requires the ship to turn almost perpendicular to the flood or ebb tidal currents. During an inbound run, the ship experiences high (2.5 knots) crosscurrents, small currents in a semiprotected channel between shoals, back to high crosscurrents, and finally minimal currents in a fully protected and confined channel. A car carrier terminal with moored ships alongside near the entrance further complicates the navigation conditions.

The simulation study (Thevenot et al. 1996)showed the 350-ft-width design should not be seriously considered. In fact, a significant increase in width is recommended from the originally considered design (Figure C-8). Some of the docking tug company pilots had difficulty adapting to the new, deeper, but narrower channel condition. They tried to use several different strategies for turning and reducing speed. The available tugs could not be used to control the ship in the 25-knot wind and strong tidal currents.

(2) Lessons learned. Safety considerations dictated a wider channel than originally planned due to the severity of local environmental conditions. Backing large ships is difficult, particularly in currents. Sometimes the operational limits may have to be adjusted, e.g., the ships may not be able to come in under high wind and currents. In some cases, it may be desirable to consider high-accuracy ship positioning information, such as in the 1,250-ft turning basin, as an alternative to size increases.

f. Oakland Harbor Navigation Study.

(1) Study Description. The Port of Oakland and the Inner and Outer Harbors are located on the eastern side of the San Francisco Bay in the Counties of Alameda and San Francisco, California (Figure C-9), Navigation problems arise from the shear or cross currents at the entrance of Inner and Outer Harbors (Figure C-10), and the size of the two harbor’s turning basins (Figure C-11). A deepening project to take the channel to –50 ft was proposed to accommodate the Extended K-class containership, to reduce tidal-caused delays associated with containership passages, and to increase navigational safety.

The most critical aspect of the deepening project was the Inner Harbor Turning Basin. Real estate concerns not only limit the size of this turning basin; but would also prefer for the size to be reduced. After lengthy validation time to ensure that the simulator was acting correctly in this critical area, the final study showed that although the turning basin could not be reduced; the pilots would be able to maneuver the new design vessels in the existing dimension basin (Figure C-12).

(2) Lessons Learned. Turning basin design based only on a multiple of a design ship length cannot be generalized without including site-specific considerations. Sometimes changes in turning basin layout can be made using the simulator and local pilots to accommodate

concerns without sacrificing navigational safety. However, these site-specific results cannot necessarily be applied to another location, even in the same port.

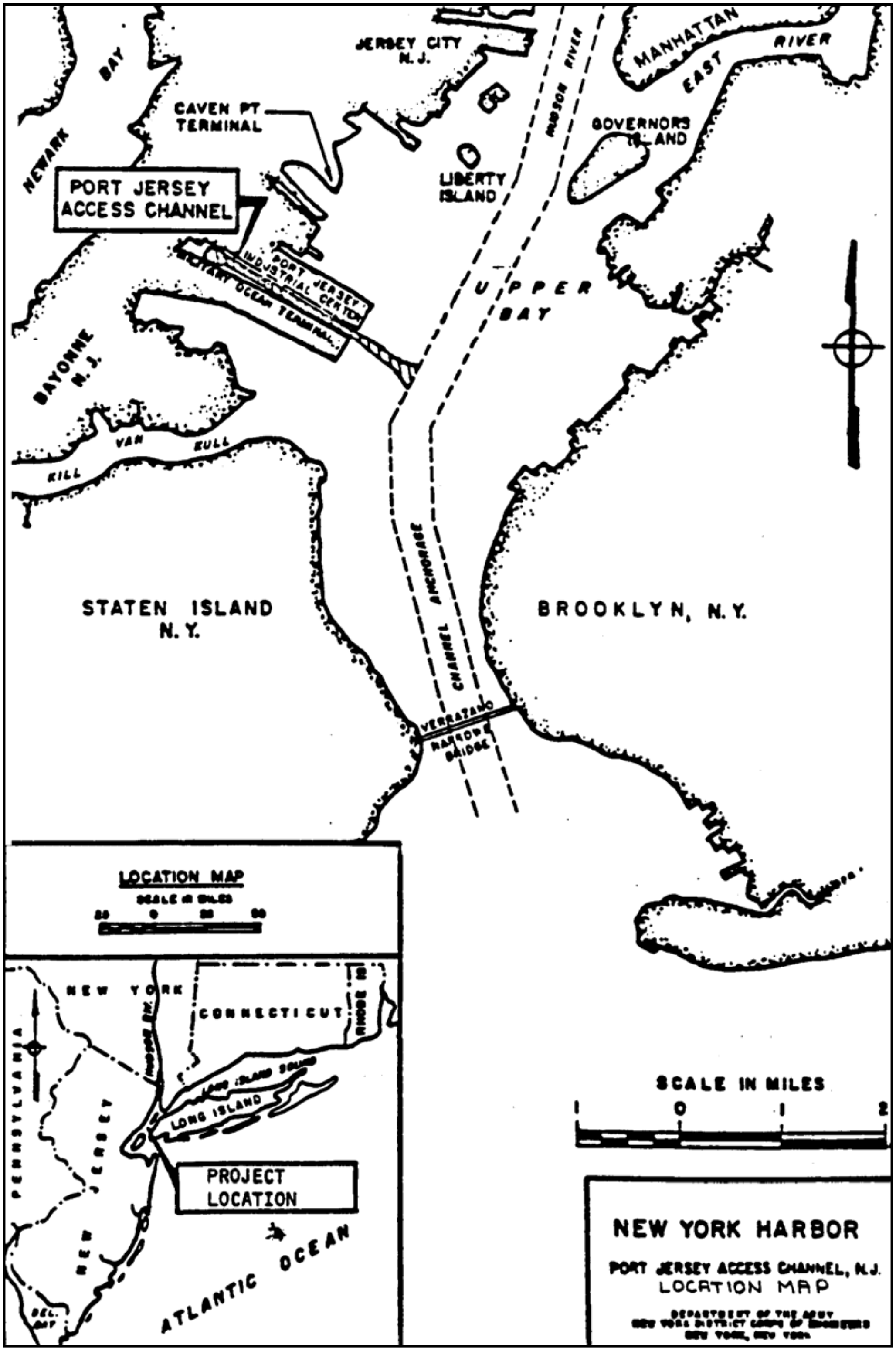

Figure C-7. Port Jersey location map

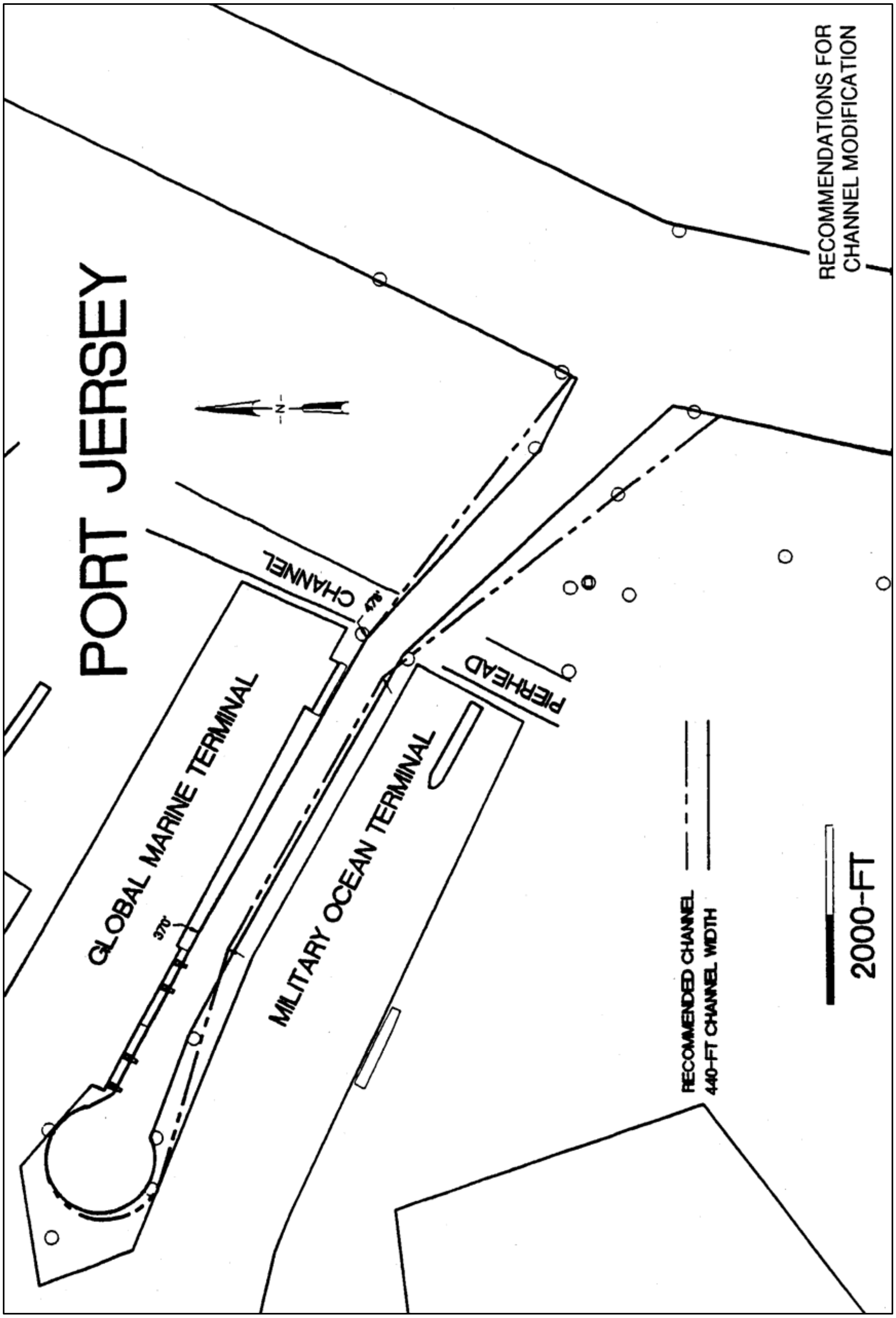

Figure C-8. Port Jersey channel modification recommendation

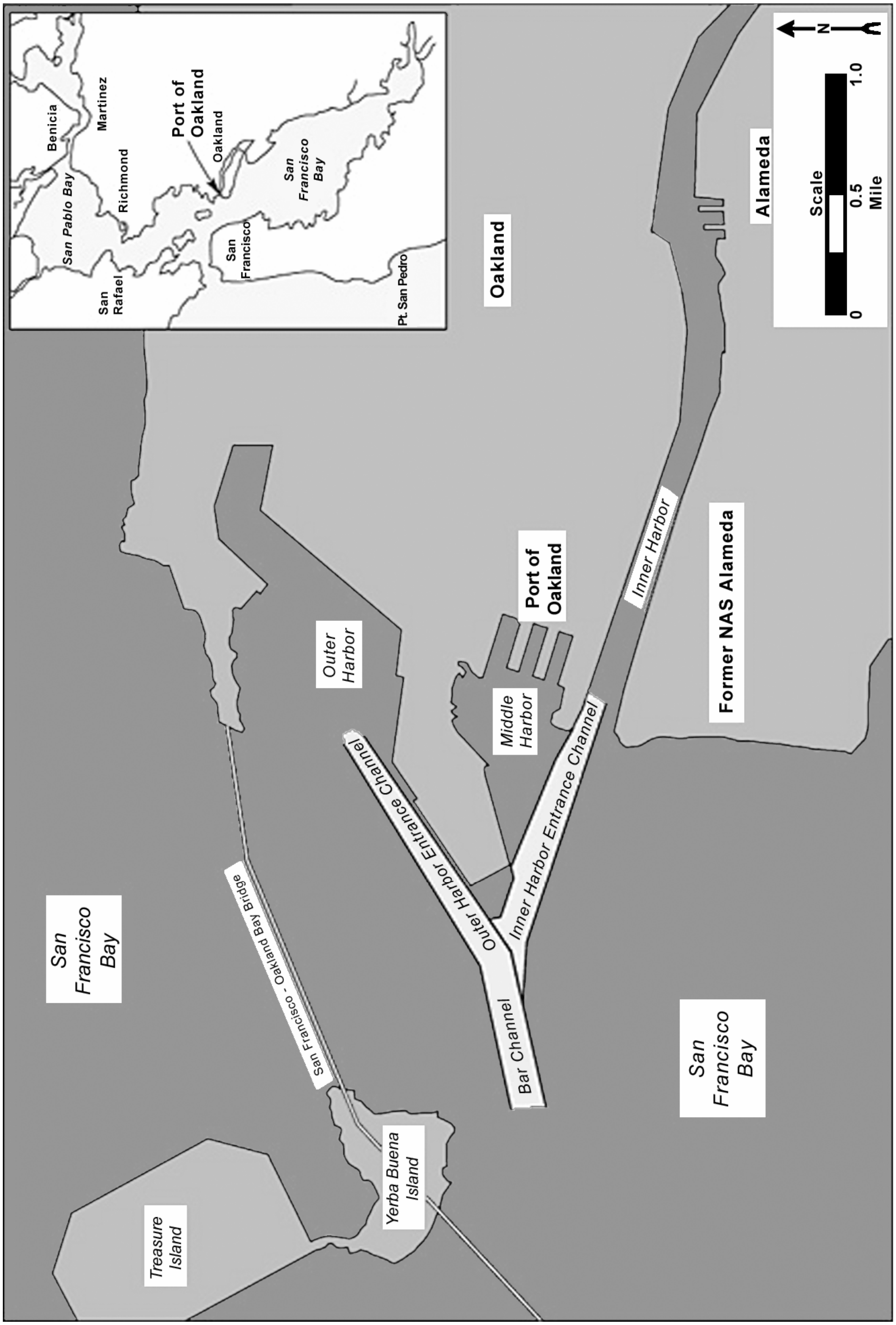

Figure C-9. Oakland Harbor location map

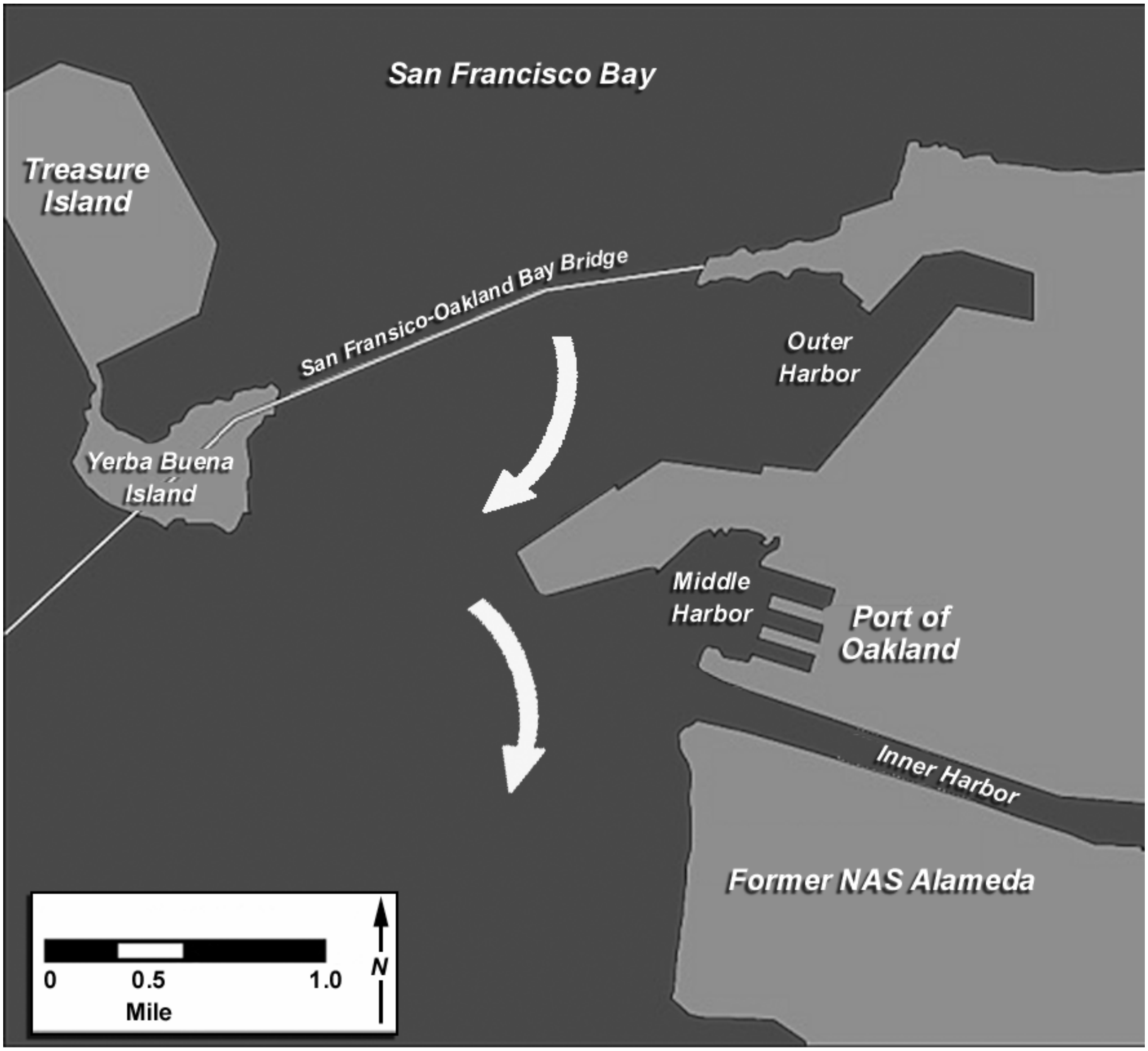

Figure C-10. Oakland Harbor – location of shear currents

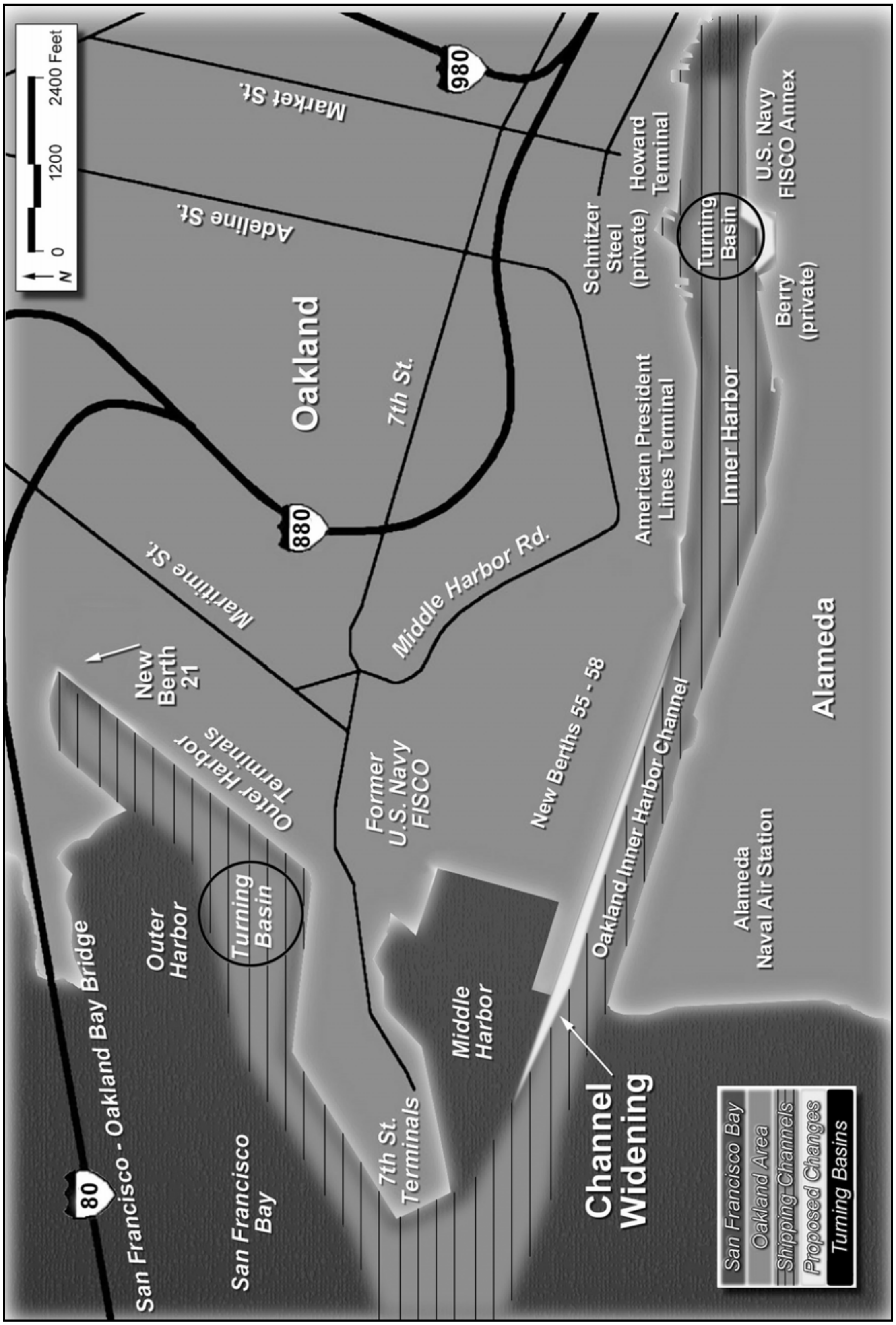

Figure C-11. Oakland Harbor – location of turning basins

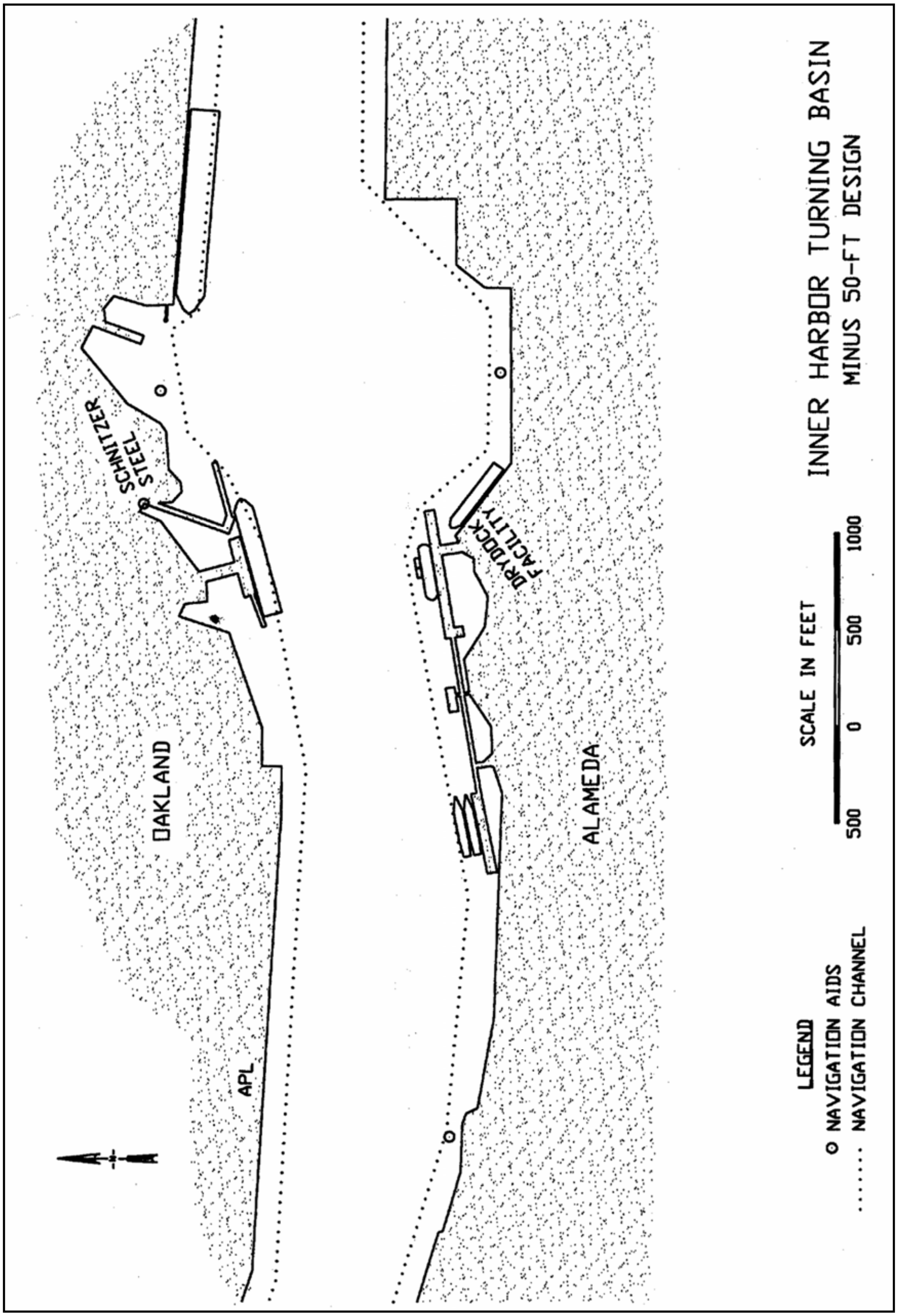

Figure C-12. Oakland Harbor Navigation Study, recommended design for Inner Harbor turning basin *g. Sacramento Ship Channel*.

(1) Study description. Cost sharing by local port authority project sponsors for navigation improvements has introduced new factors to consider into design. In fact, financial considerations, such as port revenues, can determine which, or even whether, projects will be built by the Federal Government. The Sacramento River Deepwater Channel is a project that became critical because of the high cost and marginal local port authority financing. Ninety percent of the project cost was in the man-made canal portion. This involved deepening the project from 30 to 35 ft and widening the channel from 200 to 250 ft.

Through ship simulation tests, substantial design changes were developed for the deeper channel. By widening the turns to 250 ft and providing transitions from the widened turns to the existing 200-ft-width channel, the pilots could maintain the same level of ship control as they had in the unimproved 30-ft channel. This resulted in a savings of about $20 million.

(2) Lessons learned. Ship simulation tests in highly constricted canals can be conducted but require more subjective pilot and engineer judgment. Published bank effect models of ship forces and moments are inadequate; the study led to improved modeling of the canal bank effects on the maneuvering ship. The man-made trapezoidal canal cross section had changed substantially due to local scouring. The bank effects model had to account for changing canal cross sections, which was important to realistic ship simulations.

C-5. Simulator Limitations. Bank and shallow water effects and modeling techniques are presently not well defined. More towing tank testing is needed for these important areas, especially in the range of realistic ship and channel dimensions.

Validation of ship simulation studies depends largely on the local pilot's evaluation. An improved method for obtaining validation of simulator models would go a long way to increase acceptability of channel design studies.

A lack of a generally accepted measure of safety by simulator operators is another important present limitation.

Simulation models presently all assume passive ship effects, even when the ship presence influences the flow field, such as lock approaches. Ships meeting and passing in highly restricted waterways (the so-called Texas Chicken maneuver) is another example of important ship/flow field/ship interaction. More experimental and theoretical studies are needed to quantify and develop math models of highly interactive maneuvering situations.

C-6. Conclusions. Published channel design criteria are very conservative. Channel width, turning basin, and turn widening designs can all be less than the required dimensions, provided a simulator study is used to verify the design.

Ship simulator study results have been used by ERDC/WES to substantially decrease project costs and reduce dredging material volumes on many navigation projects throughout the United States.

Channel design can be localized using a simulator to the specific project requirements. Channel size can be localized as required by simulator test results, providing width increases only where needed.

In some cases the simulator tests have resulted in improved safety and efficiency of the navigation project.

Simulator studies can be costly and time-consuming; the benefits in most cases, however, are far greater than the costs and result in safer channel designs.

Smaller, less expensive, studies (desk-top studies) can be designed to explore potential benefits and indicate the need for more extensive investigation of specific project areas.

Engineering design of navigation channels can be accomplished in a cost effective manner with limited ship simulators having modest visual scene display and bridge equipment. Accurate modeling of the ship, currents, and channel effects is important for successful channel design studies.

Simulation studies should be initiated early in the project planning process and preferably conducted in an iterative manner to ensure that an optimum design has truly been achieved.

C-7. Acknowledgements. The success of the ERDC/WES Ship Simulator would not be possible without the highly capable and dedicated team conducting the studies. We appreciate their efforts.

The tests described and the resulting data presented, unless otherwise noted, were obtained from research conducted under the Navigation Hydraulics Research Program of the United States Army Corps of Engineers and specific project studies for the respective District offices by the ERDC/WES, Vicksburg, MS. Permission was granted by the Chief of Engineers to publish this information.

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