APPENDIX C

USE OF PHYSICAL HYDRAULIC MODELS AS TOOLS IN DEEP-DRAFT ENVIRONMENTAL STUDIES

C-1. Introduction.

a. Earlier sections of this EM discuss specific considerations which must be addressed to evaluate the impacts of deep-draft navigation channels on water quality and biological or ecological conditions. One of the tools that can be (and has been) applied to make the necessary predictions of these conditions is physical hydraulic modeling. This appendix gives a brief description of physical hydraulic modeling and its relation to other methods. It is intended to familiarize engineers and scientists with the use of this technique in preparing impact studies. The relative strengths and weaknesses are discussed so that, depending on the specific situation, physical hydraulic models might be effectively considered in a modeling strategy. The basis and methods used in physical modeling are also briefly described.

b. For projects in which dependable, accurate results warrant the additional expense, a physical model study is recommended. This approach is especially recommended if the system is partially mixed or stratified in vertical salinity structure, or if it has a complicated geometry. Guidance for initiating physical (hydraulic) model studies is given in ER 1110-1-8100, ER 1110-2-1403, and related ERs. Estuarine studies performed at WES usually take 18 to 48 months and cost roughly $20 per square foot of model and $20,000 per month.

C-2. Physical Hydraulic Models.

a. Physical hydraulic models are scaled representations of a waterway area under study. Figure D-1 shows a physical model of New York Harbor. Naturally, models are at reduced scale; usually one foot (horizontal) in a model equals 500 to 1000 feet in the prototype (the actual waterway). Seawater supply, tide generators, and gaged freshwater inflows are appurtenances. The models are usually molded in concrete between closely spaced templates. Instrumentation is mounted on models or samples are drawn from them to measure such attributes as water surface elevation, current speed and direction, salinities, and tracer concentration. Tracers are often photographed to qualitatively examine their behavior or patterns of flow. Hudson et al. (1979) give a more detailed description of physical hydraulic models.

b. Boundaries and features of models should be planned carefully. A physical hydraulic model is designed and constructed to include the region of interest and other areas necessary so that boundary data or conditions can be satisfactorily applied. If the effects on assimilative capacity of the waterway are to be tested, effluent outfalls or diffusers are included in model design and construction. If all the modifications to be tested in the model are known at the time of model design, provisions can be made to make them quickly and less expensively.

Figure D-1. Physical model, New York Harbor

C-3. Comparison to Other Methods.

a. Other methods for testing large-scale physical changes, such as deep-draft channels, include testing in the prototype, analytical techniques, and numerical modeling. Prototype tests and analytical techniques are rarely employed since they tend to be impractical due to their expense or difficulty due to uncontrollable conditions. Thus, only physical hydraulic and numerical models of estuaries will be compared herein. Physical hydraulic modeling of estuaries was first used in the last century and has increased steadily in this country since the 1930s. Numerical modeling in multiple spatial domains has been practiced only since the mid-1960s. Both methods are developing. Physical hydraulic modeling has been refined by the use of automated model control and data acquisition, by advances in instrumentation, by postconstruction model evaluation, and by research on model mixing processes.

b. Physical hydraulic models have been used to study the effects of channel deepening. The have been used successfully to predict tidal currents, circulation, riverflows, salinity distributions, waste effluent dispersion, and exchange rates of estuarine environments. These conditions are a result of a number of processes, many of which are three-dimensional and nonlinear in character. If these conditions are of central concern to a study, the physical modeling approach should be considered best. Physical hydraulic models are real and therefore offer the only means of representing the region of interest as a three-dimensional continuum whose resolution is limited only by the availability of topographic data. Many of the physical processes responsible for variability in the estuarine environment can be represented in physical hydraulic models, including vertical density effects, which are important in most deep-draft studies. The strong points of physical hydraulic models when compared with numerical models are:

(1) Several processes may be evaluated in one model.

(2) Three-dimensional effects are included.

(3) Salinity can be best represented.

(4) Long simulations are practical.

(5) Operating costs are lower in some cases.

c. The last two items are related. Numerical models can be run for long periods, but this can be costly and stability problems sometimes arise. However, physical hydraulic models can also be costly. Physical hydraulic models can be operated over multiple spring-to-neap tidal cycles or with long freshwater inflow hydrographs. The importance of this capability will be discussed later. Physical models can include point source discharges and represent their behavior relatively near to this source. The major disadvantages of physical hydraulic models are their high initial cost and possible scale or scale-distortion effects on dispersive transport and bed shear stress. Construction and verification of physical models take time and are relatively expensive. To counteract scale effects, mixing is adjusted by distributing roughness or friction, in some cases, by applying supplemental mixers.

d. Cost and speed of application are advantages of numerical modeling. However, since both methods require that basically the same field data be collected, time might not be an advantage. Most numerical models are averaged in one or more dimensions and solve equations that are simplified by parameterizing mixing and dispersion processes into coefficients. These coefficients are generally unknown and change in space and time. The numerical modeler must attempt to match these coefficients to processes that are known to be scale dependent. Numerical models generally overestimate near-field or small-scale dispersion.

e. With the exception of salt concentration, the attributes and processes represented in physical hydraulic models are physical, not biological or chemical. Therefore, many complex chemical and biological systems that may be of interest in estuaries may not be represented in physical models. In many cases, physical processes dominate these conditions and deserve priority consideration. The strength of the physical modeling approach is in the representation of these processes. The strong points of the numerical approach are the ability to represent large numbers of nonconservative constituents, either chemical or biological, and to more accurately model sedimentation processes.

C-4. Modeling Practice.

a. Similitude.

(1) Similarity between the physical hydraulic model m and the prototype p must be defined so that every point in time, space, and process can be uniquely coordinated. This is done by introducing scaling laws based on the Froude number equality:

$$\text{(velocity)}^2/\text{(gravitational acceleration} \times \text{depth)} \quad (p = m)$$

and is extended by dimensional analysis of equations that apply to both the model and the prototype. A distortion can exist if two variables or parameters representing the same physical property are sufficiently independent so that they can be given different scale ratios. Physical hydraulic models of estuaries are almost always distorted in length scale such that the horizontal scale Lx and the vertical scale Lz are not equal. This is done to reduce scale effects, maintain turbulent flow in the model, and minimize model construction costs. Scale ratios p/m for some of the attributes of interest are:

$$\text{time} = \frac{Lx}{\sqrt{Lz}}$$

$$\text{horizontal velocity} = Lz^{1/2}$$

$$\text{vertical velocity} = \frac{Lz^{3/2}}{Lx}$$

$$\text{horizontal diffusion and dispersion} = Lz^{1/2}Lx$$

$$\text{vertical diffusion} = \frac{Lz^{5/2}}{Lx}$$

(Salinity/density ratios are generally taken as unity.)

(2) It may not be possible to satisfy all the similarity scaling laws, in which case other ratios are defined to describe the expected deviation in model behavior. Point source discharges, such as from outfalls and diffusers, are specially scaled in models to maintain turbulence and achieve similarity in near-field behavior.

b. Model Verification. The first step after model construction is model calibration and verification. Extensive prototype data collection and analysis programs are required to provide the information necessary for calibration or adjustment of the model. Such data should cover the range of boundary data that will be used in the testing program, as far as possible. Usually tide heights are adjusted first, followed by currents and salinity. During the verification period, model-to-prototype comparisons are made. Model repeatability is normally addressed at this point in the modeling program, which checks the assumption that the behavior of the system depends uniquely on the boundary data imposed. Small-scale mixing processes that depend on turbulence are probabilistic and will not repeat exactly.

c. Test Procedures.

(1) After the verification phase is complete, model base (no modification) and plan (modifications installed) tests are performed. Boundary data and sampling locations are selected based on some frequency of occurrence and on expected gradients, respectively. Test data routinely include water surface elevations, currents, and salinities and might also include effluent, sediment, or dye tracer concentrations, depending on the conditions being tested. Velocities, salinities, and tracer concentrations can be subjected to statistical analysis to determine the relative contributions of circulation and gradient diffusion on mixing. Tracer concentrations can also be used to estimate exchange rates, purging rates, or shoaling rates. If necessary, effluent concentrations can be analytically corrected for decay processes. In general, base tests provide an opportunity to observe model behavior and elucidate or identify patterns in this behavior, often leading to a better understanding of the dominant processes in the prototype. Plan tests then provide a measure of the impacts of the modification on the conditions of interest and the desirability of this impact.

(2) Selecting boundary data and their variability requires some consideration. Constant boundary data, such as a steady inflow and repetitive diurnal or semidiurnal tide, result in conditions varying with the tidal frequency. Data collection is simplified because it can be moved from station to station and observations will be comparable (quasisynoptic). Variable boundary data might consist of a spring-to-neap varying tide. This makes synoptic data collection more difficult. If the inflow is steady, successive neap-to-spring cycles can be sampled at different stations. If the inflow varies, a slack-water sampling scheme may be indicated. Despite these sampling problems, the variation from spring-to-neap tide causes important effects on salinity

distributions and circulations in some estuaries not observable using constant boundary data. It is recommended that spring-to-neap tidal cycles be incorporated into at least some phase of model testing.