ASCE Manuals and Reports on Engineering Practice No. 97

Hydraulic Modeling

Concepts and Practice



ASCE

AMERICAN SOCIETY OF CIVIL ENGINEERS

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Hydraulic Modeling
Concepts and Practice

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Sponsored by the
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Abstract: This Manual is intended to serve as a useful reference for people who engage in hydraulic modeling or who directly use the results obtained from hydraulic models. Early chapters provide a brief history of hydraulic modeling, outline strategies for designing models, and explain the underlying concepts of similitude and dimensional analysis. Those concepts are applied subsequently to various situations, beginning with single-phase flow of fluids; water and air are the fluids primarily considered in the Manual.

Subsequent chapters address the more complicated situations in which resort must be made to hydraulic models for engineering or technical information. One chapter covers the use of hydraulic models to investigate sediment transport by flow, especially alluvial-sediment transport, and flow in loose-boundary channels. Other chapters cover modeling of gas–liquid flows (notably air in water) and flows involving ice and debris transport. The Manual also addresses hydraulic modeling of situations it terms *environmental flows*, which essentially encompass buoyancy-modified flows (plumes, stratified flows, mixing) and flow of immiscible fluids (for instance, oil and water). Hydraulic modeling of coastal processes, hydroelastic vibrations, and hydraulic machinery are explained in chapters devoted to those topics. One chapter discusses practical aspects of designing and operating hydraulic models. The Manual's final chapter presents five case study examples.

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PREFACE

The Manual was completed by ASCE's Task Committee on Hydraulic Modeling, which was composed of the following members: R. Ettema (University of Iowa), Chairman and Editor; R. Arndt (University of Minnesota/National Science Foundation); P. Roberts (Georgia Institute of Technology); and T. Wahl (U.S. Bureau of Reclamation).

The Manual's progenitor is *ASCE Manual 25: Hydraulic Modeling*, which was written in the late 1930s and published in 1942. The primary objective of the Task Committee was to substantially update Manual 25, taking into account the significant advances in modeling methods and the broadening of hydraulic issues addressed by means of hydraulic modeling. The Committee intends that the updated Manual serve as a guide rather than be taken as a standard, which implies a certain standardization of modeling methods and materials. The Manual presents widely accepted (and some not so widely accepted) methods used in hydraulic modeling. The Committee notes that different modelers may favor variations of the methods presented, which is in keeping with the notion that engineering practice combines science and, one might say, art.

A broad range of modeling topics, issues, and techniques is covered in the Manual, whose preparation involved many people. Though considerable scope exists for further streamlining the Manual, the arrangement of its chapters is intended to provide a progression of information, yet also to enable individual chapters to stand more or less alone. This compromise attempts to serve the Manual's diverse audience; some readers may wish to work through a large portion of the Manual, while others may prefer to browse a single chapter. Mild redundancy in certain aspects of content is the price of this compromise. The Committee believes it to be a price worth paying and leaves it to a future committee to take care of streamlining found necessary.

Major contributions to chapters in the Manual were made by the Committee's members and the following people: S. Martin (Georgia Institute of

Technology), Chapter 7; J.W. Kamphuis (Queens University), Chapter 9; and G.A. Schohl (Tennessee Valley Authority), Chapter 10.

Additional contributions—written segments and/or review comments—were made by the following people: G. Cotroneo (Acres International); J. Larson (Alden Research Laboratory); A. Alsaffar (Bechtel); S. Chakrabati (Chicago Bridge and Iron Co.); H.T. Shen and P. Yapa (Clarkson University); P. Julien (Colorado State University); P. Hopping (Tennessee Valley Authority); J. Aguirre-Pe (Universidad de los Andes); E. Macagno, M. Muste, and L. Weber (University of Iowa); M. Lambert (University of Adelaide); P. Tullis (Utah State University); J.E. Zufelt (U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory); R. Davinroy (U.S. Army Corps of Engineers, St. Louis District); and S. Maynord, N. Pachure, and T. Pokrefke (U.S. Army Corps of Engineers, Waterways Experiment Station). M. Kundert and A. Kruger (University of Iowa) helped prepare the Manual's figures.

The draft monograph was reviewed by S. Abt (Colorado State University), J. Bradley (West Consultants, Inc.), P. Burgi (U.S. Bureau of Reclamation), G. Hecker (Alden Research Laboratory), and S. C. Jain and T. Nakato (University of Iowa).

G. Gartrell (Contra Costa Water District), W. Frizell (U.S. Bureau of Reclamation), and T. Nakato (University of Iowa) were the contact members for ASCE's Technical Committee on Hydraulic Measurements and Experimentation, which formed the Task Committee.

NOTATION

A	area; dependent variable
A_W	surface area exposed to wind
a	acceleration; a constant; wave height amplitude
a_B	bottom orbital amplitude of waves
a_{su}	step-up coefficient
a_δ	thickness of boundary layer formed by oscillatory motion beneath a wave
B	width of structure (e.g., a pier); function
B_d	a coefficient dependent on particle size
B_o	ratio of electrostatic forces and buoyancy force acting on an ice particle
C	Chézy resistance coefficient; chord length; celerity of interfacial wave
Ca	cavitation number
Ca_d	desinent Ca
Ca_i	incipient Ca
Ca_T	Thoma's sigma
C_D	drag coefficient; discharge coefficient
C_{DW}	drag coefficient associated with wind blowing over a surface
C_f	friction coefficient, $(u_* / U)^2$
Ch	Cauchy number
C_L	lift coefficient
C_M	virtual mass (or added mass) coefficient
C_m	coefficient expressing the relationship between units of measure
Cp	Capillary number
C_P	pressure coefficient
C_s	speed of sound
c	constant; wave celerity
c_p	specific heat
D	pipe diameter; pier diameter; pump-bell diameter; impeller diameter; bubble diameter

D_E diameter of effluent nozzle
D_f molecular diffusion coefficient
d diameter of cylinder; particle diameter
d_n nozzle diameter
d_S depth of local scour
d_{50} median particle diameter
d_* dimensionless particle diameter
E elastic modulus
Ec Eckert number
$Eö$ Eötvos number
Eu Euler number
F_D drag force
F_e electrostatic force
F_g particle-weight force
F_L lift force
Fr Froude number
Fr_D densimetric Froude number
Fr_j jet Froude number
f Darcy–Weisbach resistance coefficient
G geometric distortion, X_r/Y_r
G_n natural distortion
g gravity acceleration
g' modified gravity acceleration, $g(\Delta\rho/\rho_o)$
g_S mass rate of sediment transport per unit width of flow
H pressure head; wave height; net head across machine
H_{ia} heat transfer coefficient for ice to air heat exchange
H_L head loss
H_o deepwater wave height
h flow depth above spillway crest; thickness of accumulated ice
h oil slick thickness
h_a atmospheric pressure head
h_{LE} thickness of leading edge of slick
J specific-heat ratio
K surface heat transfer coefficient; structural spring stiffness; conveyance coefficient
k roughness height, C_p/C_v; wave number = $2\pi/\lambda$
k_0 neutral Rankine pressure-state coefficient
k_1 passive Rankine pressure-state coefficient
k_1, k_2 coefficients
L length; flow length; wave length
l_g characteristic length of generator
M mass; a non-dimensional parameter
Ma Mach number
m mass; beach slope

m_s structural vibrating mass
N buoyancy frequency; impeller rotational speed
N_k surface heat transfer coefficient
N_s specific speed
n Manning resistance coefficient
P power
P wetted perimeter
P electrostatic bond force between particles
Pn Property number
Pr Prandtl number
P_w wind drag force
p pressure; porosity
p_a atmospheric pressure
p_o reference pressure
p_v vapor pressure
Q discharge; water discharge
Q_{air} air discharge
Q_{E} entrained flowrate
Q_{max} full siphon flow
Q_0 gas volumetric flow rate
q discharge per unit width of flow
q_S volumetric rate of sediment transport per unit width of flow
R hydraulic radius
Rd Reynolds number based on bubble diameter
Re Reynolds number
Re_d Reynolds number associated with flow around drifting debris
Re_D Reynold number based on pump-bell diameter and inflow rate
Re_j jet Reynolds number
Re_R Reynolds number based on pump-bell radius and inflow rate
Re_s spill Reynolds number
Re_* particle Reynolds number
R_h hydraulic radius
Ri gradient Richardson number
bulk Richardson number
Ro Rossby number
r radius
r_c critical radius
r_e equilibrium radius
S slope; submergence of pump bell
Sc Schmidt number
S_f friction slope
S_G generator stroke
So Stokes number
St Strouhal number

T time; temperature; tensile strength of a liquid; wave period
t time
t_{Sr} time scale for sediment transport
U streamwise flow velocity
U_{LE} velocity of leading edge of a slick
u local velocity in x direction
u_d drift velocity of debris
u_j jet velocity
u_s slip velocity
u_* shear velocity
u_{*c} critical value of u_* associated with incipient motion of bed particles
V mean velocity of flow
V_C crossflow velocity
V_E flow velocity across entrainment interface; effluent velocity from outfall
V_n velocity of effluent flow
V_W wind velocity
v local velocity in y direction
$\forall$ volume
We Weber number
w local velocity in z direction; fall velocity of a sediment particle
x horixontal scale
Y flow depth; vertical scale; water depth
Y_b depth at which waves break
y depth
y_o particular amplitude
z distance

GREEK SYMBOLS

α angle; plume entrainment coefficient; thermal diffusion coefficient
α_b incident wave angle
β expansion coefficient; Henry's constant
Γ flow circulation
γ specific weight
Δ increment
δ bedform height
ε mean ice roughness
$\varepsilon_v, \varepsilon_t$ vertical and transverse diffusion coefficients
ζ damping parameter
η displacement from equilibrium position; efficiency
θ Shields parameter; temperature
Λ percentage of power losses in turbomachinery operation

λ wave length; bed form length; ratio of the effective buoyancy width to the effective momentum width within a plume
μ dynamic viscosity; internal resistance coefficient for floating ice rubble
ν kinematic viscosity
ν_g kinematic viscosity of gas
ν_l kinematic viscosity of liquid
ξ added-mass parameter; radiation stress
Π dimensionless pi number
π pi (3.14)
ρ density
ρ_a density of air
ρ_d density of debris
ρ_g density of a gas
ρ_i density of ice
ρ_l density of a liquid
ρ_o reference or ambient density
ρ_s density of sediment particles; structural material density
σ stress; strength; surface tension strength of water
σ_f flexural strength
τ shear stress
Φ dimensionless bedload sediment transport rate
ϕ angle of internal resistance
ϕ_c Shields entrainment
φ functional relationship among nondimensional parameters
Ω local angular velocity of the earth
ω frequency; frequency of oscillation; angular velocity

SUBSCRIPTS

b value at solid boundary
p prototype
m model
r ratio

Chapter 1
INTRODUCTION

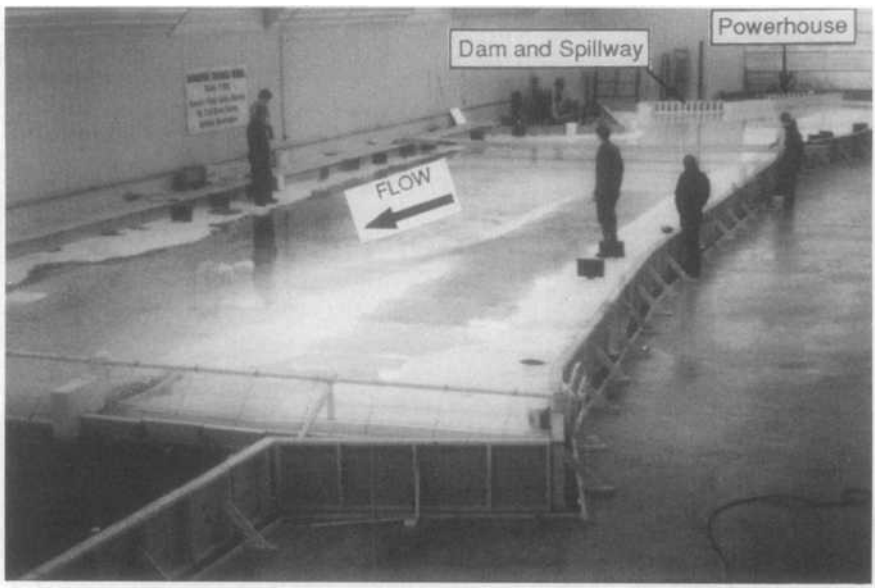
1.1 HYDRAULIC MODELING

Hydraulic modeling is a form of physical modeling widely used to investigate design and operation issues in hydraulic engineering. It entails, with a degree of sophistication that varies with the objective of the investigation, the use of a scaled model for replicating flow and fluid-transport processes in diverse natural flow systems and for evaluating the performance of hydraulic structures and hydraulic machines. The following situations are common subjects for modeling: water movement and sediment transport in rivers and coastal zones; the hydraulic performance of water intakes, spillways, and outlets; flow around various objects; flow through, or in, various conduits or flow-regulating devices; performance of turbines, pumps, and other hydromachines; performance of floating structures or ships; and effluent-mixing processes.

An advantage of a hydraulic model is its potential capacity to replicate many features of a complicated flow situation. Figure 1-1(a), for instance, shows a hydraulic model of the river reach downstream of the hydropower dam illustrated in Figure 1-1(b). The model was needed to identify an optimal location, in terms of velocity distribution, for releasing salmon smolt bypassed downstream around the dam's turbines. The location could not be identified as reliably by other means because of the need to identify eddies and other three-dimensional flow features where predator fish might lurk.

There are many situations for which there is little recourse other than hydraulic modeling to make design or operational decisions involving expensive and complex hydraulic works. Such situations particularly arise when, for a variety of reasons, complex flow patterns or intricate transport processes are involved, and reliable answers cannot be obtained by means of analytical solution or computer simulation. For example, the diverse situations of local scour of alluvial bed sediment around piers,

(a)



(b)

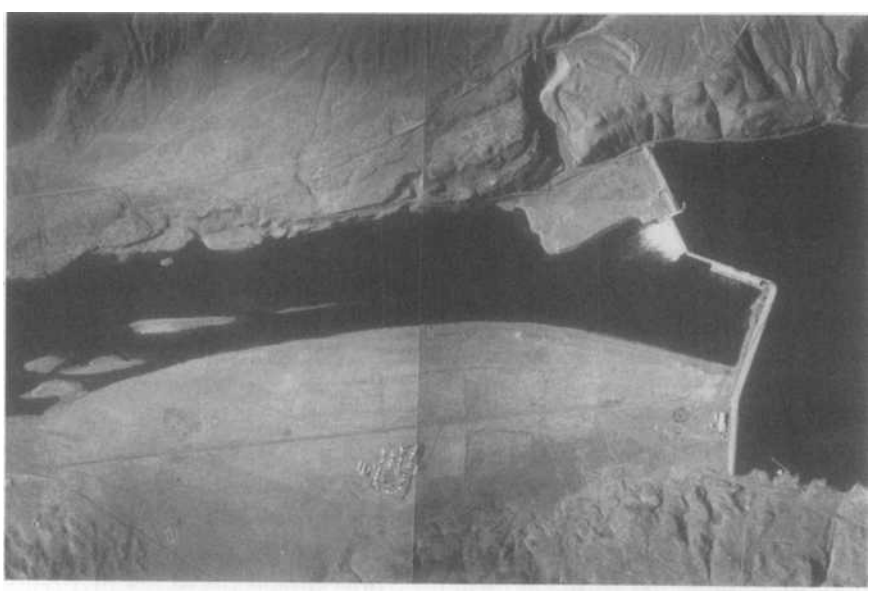


FIGURE 1-1. (a) A 100:1-scale model of a reach of the Columbia River downstream of Wanapum Dam and Hydropower Facility. (b) Aerial view of the Columbia River reach simulated in (a).

submerged pipelines, and other hydraulic structures comprise a set of situations for which hydraulic modeling has been the only means to obtain substantial insight and engineering design recommendations. The complexity of the flow and sediment movement around a cylindrical pier partially exposed at a scour hole in an erodible alluvial bed, as illustrated in Figure 1-2, is still beyond the capability of computational fluid dynamic codes. As with many local-scour situations, the flow is highly three-dimensional and contains unsteady and interacting vortices, and its bottom boundary is loose.

Hydraulic modeling of water-intake performance comprises another set of situations in which great reliance is placed on hydraulic modeling. Pump-sump flows also are markedly three-dimensional and, if poorly designed, may involve an undesired multiphase flow of air and water spun in vortices, as depicted in Figure 1-3. Additionally, pump-sump flows may be complicated by the presence of assorted structural elements within the intake. For some design purposes, notably the design of water intakes for hydropower stations and thermal power stations, engineering practice still requires testing by means of a hydraulic model rather than a numerical model. Over the years, and arguably because of flow complexity, hydraulic modeling has become the accepted method for proving the design performance of many hydraulic structures. Hydraulic models, however, are increasingly being used in combination with computational models to investigate difficult flow situations that each modeling method alone would be inadequate to address. These combined modeling techniques are discussed in Section 1.6, which outlines modeling strategies.

Besides direct use to produce information that cannot be reliably obtained by some other means for design or operational purposes, hydraulic models have additional benefits. They may provide relatively inexpensive insurance, reducing the uncertainty associated with a design or an operational procedure. A comparatively small investment in a

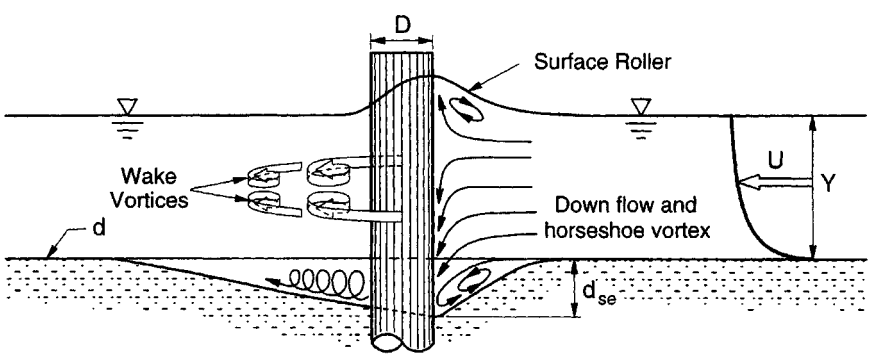


FIGURE 1-2. Flow around a cylindrical pier in an erodible loose bed.

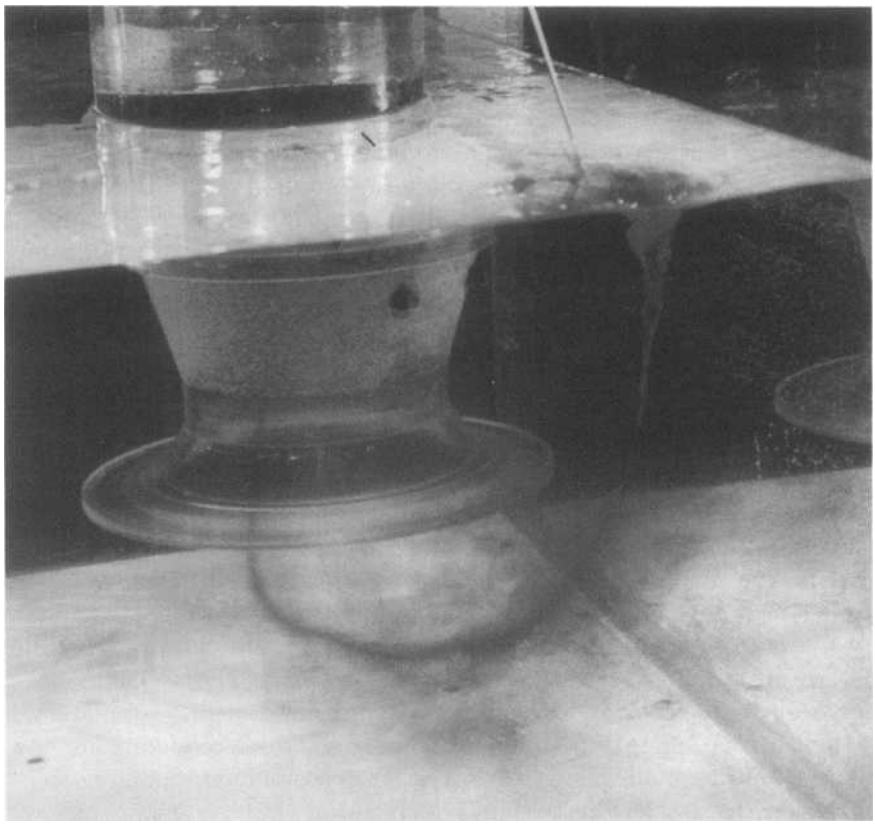


FIGURE 1-3. Flow at the bell entrance to a vertical pump in a water-intake sump.

hydraulic model study, especially in the case of expensive constructed works, may help allay concerns regarding the viability of a design or a procedure. Typically, the cost of a model study is insignificant compared to the cost of the actual installation, herein (and usually) called the *prototype* or *full-scale installation*. A hydraulic model also can be useful for public relations purposes, demonstrating to the lay person as well as the skeptical engineer how a design or a procedure will function. It usually is a convenient device for communicating complex hydraulic ideas.

Hydraulic models are sometimes differentiated in terms of their intended use. They are often used to illuminate generic physical processes. They also are used for investigating specific problem situations or for developing and performance-testing the design of a particular hydraulic structure. Some articles on hydraulic modeling (e.g., Kobus 1980, Kamphuis 1991) accordingly characterize models as *process models* or *design models*, to distinguish the two types. Design models simulate actual complex prototype situations to provide specific information for design use or

in retrospective study of failures. Examples are models to determine the effects of proposed construction, such as dams and navigation channels, on estuarine flows and salinity; models of accretion and erosion near harbor entrances; outfall models simulating effluent plumes, perhaps in stratified tidal flow; and models of breakwater stability. Process models are intended to simulate a specific generic physical process, such as how fluid stratification affects sedimentation in an estuary, how bedform ripples and flow vortices are related and how they move sediment up into the water column, or how wind waves influence dispersion. Boundary conditions and scales in process models are more abstract and can be specified to minimize laboratory and scale effects. Both classes of models rely on similitude principles to replicate prototype effects and processes and, when required, to generalize results.

The similitude principles that form the basis for hydraulic modeling are fairly straightforward. However, a difficulty incurred with preparation of a manual on hydraulic modeling is determining the extent of background information needed to adequately present the similitude criteria. A very diverse range of flow or dynamic situations is treatable using hydraulic modeling. Though an attractive feature of hydraulic modeling is that similitude principles and criteria are readily understood, their implementation may require a sound understanding of the underlying physical processes and recognition of a model's capacity to replicate those processes.

Few models exactly replicate all the processes involved with a particular flow situation. Shortcomings in models usually are termed *scale effects* or *laboratory effects*. The former term describes the incomplete satisfaction of a full set of similitude criteria associated with a particular situation. Scale effects increase in severity as the ratio of prototype to model size increases or the number of physical processes to be replicated simultaneously increases. Laboratory effects arise because limitations in space, model constructability, or instrumentation impede precise replication or measurement. They also arise from incorrect replication of boundary conditions.

Ever since the establishment of hydraulic laboratories, there has been a trend for more accurate quantitative information from hydraulic models. This trend has required refinement of similitude criteria for improved definition of processes, as well as finding means to overcome practical constraints, such as being limited largely to one model liquid (water). It also has required innovative efforts to overcome some of the restrictions imposed by laboratory facilities, such as limits in space and instrumentation capabilities. In short, there has been an effort to ensure that model results can be trusted without putting undue faith in the modeler. One indication of this trend, which continues, is the fairly recent publication of quite a few substantial volumes dealing with scaling of hydraulic models, including Kobus (1980), Novak and Cábelka (1981), Martins (1989), Shen (1990), Hughes (1993), and Chakrabarti (1994).

Significant improvements have been made in laboratory equipment and modeling methodology. Many of the improvements have been facilitated by the computer and ancillary electronic instrumentation. For example, during only a few years, wave generation for coastal or offshore models has gone from paddle-generated regular waves, through long crested irregular waves, to directional seas. It now also is possible to suppress unwanted long wave activity. Dalrymple (1989) talks about "designer" waves, in which the computer program driving the directional wave generator takes into account the reflections off the side walls of the basin to produce a prescribed wave at the structure to be tested.

1.2 PURPOSE OF THE MANUAL

The Manual is intended to be a useful reference for the hydraulic engineer conducting a hydraulic model study and for the sponsor or client of a hydraulic model study wishing to become conversant with the concepts supporting model design and operation.

The information contained in the Manual reflects the current (1999) state of the art in hydraulic modeling theory and practice. However, the point must be made that considerable skill and judgment often are needed to conduct a hydraulic model study. Indeed, the need to use a hydraulic model is an admission that the flow situation under investigation is beyond the resolving capabilities of available analytical or computer simulation techniques. In this regard, therefore, the ability of the modeler to design an effective model and to interpret the information it yields are at least as important to the success of a model study as the formal similitude criteria prescribed for modeling.

The Manual is not intended to give encyclopedic coverage of hydraulic modeling practice. To do so would be at the cost of readability and of accessibility to guiding advice for modeling. The ideal followed in preparing the Manual is that it be easily readable and well illustrated with examples and pictures. The Manual presents contemporary topics in hydraulics, such as those encompassed by the broad embrace of environmental hydraulics, and also covers enduring hydraulic topics, such as alluvial-river behavior. Neither is the Manual intended to give "standard" prescriptions for modeling various flows or to give emphatic "rules" for modeling practice. In keeping with Sharp's (1981) apt characterization of hydraulic modeling as "an art based on science," the modeler must be permitted sufficient discretion to design and work with a model that best provides the answers sought for the funds, time, and space available, and under conditions with which the modeler is reasonably familiar.

The Manual is intended to be a substantial update of *ASCE Manual 25: Hydraulic Modeling*, which was published in 1942. Since the original Man-