Sediment Transport Modeling Review—Current and Future Developments

Athanasios N. (Thanos) Papanicolaou

Associate Professor, Univ. of Iowa, IIHR-Hydroscience and Engineering, Dept. of Civil and Environmental Engineering, Iowa City, IA 52241. E-mail: apapanic@engineering.uiowa.edu

Mohamed Elhakeem

Research Associate Engineer, Univ. of Iowa, IIHR-Hydroscience and Engineering, Dept. of Civil and Environmental Engineering, Iowa City, IA 52241. E-mail: melhakee@engineering.uiowa.edu

George Krallis

ERM Inc., Exton, PA. E-mail: george.krallis@erm.com

Shwet Prakash

ERM Inc., Exton, PA

John Edinger

Faculty Research Associate, Bryn Mawr College, Dept. of Geology. E-mail: jeedgr@aol.com

Introduction

The use of computational models for solving sediment transport and fate problems is relatively recent compared with the use of physical models. Several considerations govern the choice between physical and computational models; namely, the nature of the problem that needs to be solved, the available resources, and the overall cost associated with the problem solution. In some specific problems, a combination of physical and computational models can be used to obtain a better understanding of the processes under investigation (de Vries 1973). Using computational hydrodynamic/sediment transport models, in general, involves the numerical solution of one or more of the governing differential equations of continuity, momentum, and energy of fluid, along with the differential equation for sediment continuity. An advantage of computational models is that they can be adapted to different physical domains more easily than physical models, which are typically constructed to represent site-specific conditions. Another advantage of computational models is that they are not subject to distortion effects of physical models when a solution can be obtained for the same flow conditions (identical Reynolds and Froude numbers, same length scale in the three directions, etc.) as those present in the field.

With the rapid developments in numerical methods for fluid mechanics, computational modeling has become an attractive tool for studying flow/sediment transport and associated pollutant fate processes in such different environments as rivers, lakes, and coastal areas. Representative processes in these environments include bed aggradation and degradation, bank failure, local scour around structures, formation of river bends, fining, coarsening and armoring of streambeds, transport of point source and nonpoint source pollutant attached to sediments, such sediment exchange processes as settling, deposition, and self-weight consolidation; coastal sedimentation; and beach processes under tidal currents and wave action.

Over the past three decades, a large number of computational hydrodynamic/sediment transport models have been developed (Fan 1988; Rodi 2006). Extensive reviews of different hydrodynamic/sediment transport models can be found in Nicollet (1988), Nakato (1989), Onishi (1994), Przedwojski et al. (1995), Spasojevic and Holly (2000), and the ASCE Sedimentation Engineering Manual no. 110 (2007). Broadly speaking, these models can be classified on the basis of the range of their applications (e.g., suspended load versus bed-load; physical versus chemical transport); and their formulation in the spatial and temporal continua (e.g., one-dimensional model (1D); two-dimensional model (2D); or three-dimensional model (3D); and steady versus unsteady). The choice of a certain model for solving a specific problem depends on the nature and complexity of the problem itself, the chosen model capabilities to simulate the problem adequately, data availability for model calibration, data availability for model verification, and overall available time and budget for solving the problem.

The objectives of this article are twofold. First, the article aims to trace the developmental stages of current representative (1D, 2D, and 3D) models and describe their main applications, strengths, and limitations. The article is intended as a first guide to readers interested in immersing themselves in modeling and at the same time sets the stage for discussing current limitations and future needs. Second, the article provides insight about future trends and needs with respect to hydrodynamic/sediment transport models. In preparing this article, the authors may have unintentionally omitted some models, since including all the available models found in the literature is impossible. Finally, this article is mainly focused on multidimensional computational models (2D and 3D models); however, a brief overview of the 1D models is also included for providing a rational comparison of the 1D model features with the main features of the 2D and 3D models.

Description of Models

This section provides information about the model formulation, the spatial and temporal characteristics, the coupling/linkage of the hydrodynamic and sediment components, and the model's predictive capabilities. Tables 1–3 complement this description by providing useful information about the model capabilities to handle unsteady flows, bed load and suspended load, sediment exchange processes, type of sediment (cohesive versus cohesionless), and multifractional sediment transport. Information about model acronyms, language, availability, and distribution is also provided in Tables 1–3. Tables 4–6 summarize examples of the different model applications. The reader can use these case stud-

Table 1. Summary of Selected 1D Models

Model and references	Last update	Flow	Bed sediment transport	Suspended sediment transport	Sediment mixtures	Cohesive sediment	Sediment exchange processes	Executable	Source code	Language
HEC-6: Hydraulic Engineering Center; Thomas and Prashum (1977)	V. 4.2 (2004)	Steady	Yes	Yes	Yes	No	Entrainment and deposition	PD	PD	F77
MOBED: MObile BED; Krishnappan (1981)	—	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	C	C	F90
IALLUVIAL: Iowa ALLUVIAL; Karim and Kennedy (1982)	—	Quasi-steady	Yes	Yes	Yes	No	Entrainment and deposition	C	C	FIV
FLUVIAL 11; Chang (1984)	—	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	C	P	FIV
GSTARS: Generalized sediment transport models for alluvial River simulation (Molinas and Yang, 1986)	V. 3 (2002)	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	PD	PD	F90/95
CHARIMA: Acronym of the word CHARiage which means bedload in French Holly et al. (1990)	—	Unsteady	Yes	Yes	Yes	Yes	Entrainment and deposition	C	C	F 77
SEDICOUP: SEDIment COUPled; Holly and Rahuel (1990)	—	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	C	C	F77
OTIS: One-dimensional transport with inflow and storage; Runkel and Broshears (1991)	V. OTIS-P (1998)	Unsteady	No	Yes	No	No	Advection-diffusion	PD	PD	F 77
EFDC1D: Environmental fluid dynamics code; Hamrick (2001)	—	Unsteady	Yes	Yes	Yes	Yes	Entrainment and deposition	PD	PD	F77
3STD1, steep stream sediment Transport 1D model; Papanicolaou et al. (2004)	—	Unsteady	[a]Yes	[a]Yes	Yes	No	Entrainmentand deposition	C	P	F90

Note: V=version; C=copyrighted; LD=limited distribution; P=proprietary; PD=public domain; and F=FORTRAN.
[a]Treated as a total load without separation.

ies as a reference guide for model setup, calibration, and verification.

One-Dimensional Models

Since the early 1980s, 1D models have been used with some success in research and engineering practice. Most of the 1D models are formulated in a rectilinear coordinate system and solve the differential conservation equations of mass and momentum of flow (the St. Venant flow equations) along with the sediment mass continuity equation (the Exner equation) by using finite-difference schemes. Some representative models that are developed on the basis of the previously mentioned equations include MOBED by Krishnappan (1981), IALLUVIAL by Karim and Kennedy (1982), CHARIMA by Holly et al. (1990), SEDICOUP by Holly and Rahuel (1990), 3ST1D by Papanicolaou et al. (2004). The HEC-6 formulation by Thomas and Prashum (1977) is also presented in a rectilinear coordinate and is discretized by using finite-difference schemes; but it solves the differential conservation equation of energy instead of the momentum equation.

Among other 1D models that use different coordinate systems, equations or schemes of solution are FLUVIAL 11 by Chang (1984), GSTARS by Molinas and Yang (1986), and OTIS by Runkel and Broshears (1991). Chang (1984) used a curvilinear coordinate system to solve the governing equations of his model. Molinas and Yang (1986) implemented the theory of minimum stream power to determine the optimum channel width and geometry for a given set of hydraulic and sediment conditions. Runkel and Broshears (1991) modified the 1D advection-diffusion equation with additional terms to account for lateral inflow, first-order decay, sorption of nonconservative solutes, and transient storage of these solutes.

Most of the 1D models that are presented here can predict the basic parameters of a particular channel, including the bulk-velocity, water surface elevation, bed-elevation variation, and sediment transport load. All of them, except OTIS, can also predict the total sediment load and grain size distribution of nonuniform sediment. 3ST1D by Papanicolaou et al. (2004) cannot differentiate the total sediment load into bed load and suspended load. HEC-6 by Thomas and Prashum (1977) and IALLUVIAL by Karim and Kennedy (1982) are not applicable to unsteady flow conditions. Table 1 contains the complete model reference and acronym explanation and summarizes the main features for each model.

Some of these 1D models have additional specific features. HEC-6 by Thomas and Prashum (1977), for example, decomposes energy losses into form loss and skin friction loss. MOBED by Krishnappan (1981) can predict the sediment characteristics of a streambed as a function of time and distance for different flow hydrographs. FLUVIAL 11 by Chang (1984) accounts for the presence of secondary currents in a curved channel by adjusting the magnitude of the streamwise velocity. The same model can predict changes in the channel bed profile, width, and lateral migration in channel bends. CHARIMA by Holly et al. (1990) and

Table 2. Summary of Selected 2D Model

Model and references	Last update	Flow	Bed sediment transport	Suspended sediment transport	Sediment mixtures	Cohesive sediment	Sediment exchange processes	Executable	Source code	Language
SERATRA: SEdiment and RAdionuclide TRAnsport; Onishi and Wise (1982)	—	Unsteady	[a]Yes	[a]Yes	No	Yes	Advection-diffusion	C	C/LD	FIV
SUTRENCH- 2D: SUspended sediment transport in TRENCHes; van Rijn and Tan (1985)	—	Quasi steady	[a]Yes	[a]Yes	No	No	Advection-diffusion	C	LD	F90
TABS-2; Thomas and McAnally (1985)	—	Unsteady	[a]Yes	[a]Yes	No	Yes	Entrainment and deposition	C	C	F77
MOBED2: MObile BED; Spasojevic and Holly (1990a)	—	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	C	C	F77
ADCIRC: ADvanced CIRCulation; Luettich et al. (1992)	—	Unsteady	[a]Yes	[a]Yes	No	Yes	Advection-diffusion	C/LD	C/LD	F90
MIKE 21: Danish acronym of the word microcomputer; Danish Hydraulic Institute (1993)	—	Unsteady	[a]Yes	[a]Yes	No	Yes	Entrainment and deposition	C	P	F90
UNIBEST- TC: UNIform BEach Sediment Transport—Transport Cross-shore; Bosboom et al. (1997)	—	Quasi-steady	[a]Yes	[a]Yes	No	No	Entrainment and advection	C	LD	F90
USTARS: Unsteady Sediment Transport models for Alluvial Rivers Simulations; Lee et al. (1997)	—	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	P	P	F90
FAST2D: Flow Analysis Simulation Tool; Minh Duc et al. (1998)	—	Unsteady	Yes	Yes	No	No	Entrainment and deposition	LD	P	F90
FLUVIAL 12; Chang (1998)	—	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	C	P	F77
Delft 2D; Walstra et al. (1998)	—	Unsteady	Yes	Yes	No	Yes	Advection-diffusion	C	LD	F90
CCHE2D: The National Center for Computational Hydroscience and Engineering; Jia and Wang (1999)	V. 2.1 (2001)	Unsteady	Yes	Yes	Yes	No	Advection-diffusion	PD/C	LD	F77/F90

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[a]Treated as a total load without separation.

OTIS by Runkel and Broshears (1991) can treat transport and fate of conservative contaminants and heat. EFDC1D by Hamrick (2001) can be applied to stream networks. 3ST1D by Papanicolaou et al. (2004) is capable of capturing hydraulic jumps and simulating supercritical flows; therefore, it is applicable to unsteady flow conditions that occur over transcritical flow stream reaches, such as flows over step-pool sequences in mountain streams.

Because of their low data, central processor unit (CPU) requirements, and simplicity of use, 1D models remain useful predictive tools even today, especially in consulting, for rivers and stream ecological applications where 2D or 3D models may not be needed and are computationally expensive. Table 4 presents examples of different 1D model applications.

Two-Dimensional Models

Since the early 1990s, there has been a shift in computational research toward 2D models. Most of the 2D models are currently available to the hydraulic engineering community as interface-based software to allow easy data input and visualization of results. This added capability has made these models user-friendly and popular. 2D models are depth-averaged models that can provide spatially varied information about water depth and bed elevation within rivers, lakes, and estuaries, as well as the magnitude of depth-averaged streamwise and transverse velocity components. Most 2-D models solve the depth-averaged continuity and Navier-Stokes equations along with the sediment mass balance equation with the methods of finite difference, finite element, or finite volume. Table 2 shows the complete model reference and explanation of the model acronym and summarizes the characteristics of selected 2D hydrodynamic/sediment transport models. The main specific features of each model are described below:

SERATRA: A finite-element sediment-contaminant transport model developed by Onishi and Wise (1982). The model includes general advection-diffusion equations and incorporates sink/source terms. The model can predict overland (terrestrial) and in-stream pesticide migration and fate to assess the potential short- and long-term impacts on aquatic biota in receiving streams.

SUTRENCH-2D: A finite-volume hydrodynamic and sediment transport model developed by van Rijn and Tan (1985) for simu-

Table 3. Summary of Selected 3D Models

Model and references	Last update	Flow	Bed sediment transport	Suspended sediment transport	Sediment mixtures	Cohesive sediment	Sediment exchange processes	Executable	Source code	Language
ECOMSED: Estuarine, Coastal, and Ocean Model—SEDiment transport; Blumberg and Mellor (1987)	V. 1.3 (2002)	Unsteady	[a]Yes	[a]Yes	No	Yes	Entrainment and deposition	PD	PD	F77
RMA-10: Resource Management Associates; King (1988)	—	Unsteady	[a]Yes	[a]Yes	No	Yes	Entrainment and deposition	C	P	F77
GBTOXe: Green Bay TOXic enhancement; Bierman et al. (1992)	—	Unsteady	No	Yes	No	Yes	Entrainment and deposition	NA	NA	F77
EFDC3D: Environmental Fluid Dynamics code; Hamrick (1992)	—	Unsteady	Yes	Yes	Yes	Yes	Entrainment and deposition	PD	P	F77
ROMS: Regional Ocean Modeling System; Song and Haidvogel (1994)	V. 1.7.2 (2002)	Unsteady	Yes	Yes	Yes	No	Entrainment and deposition	LD	LD	F77
CH3D-SED: Computational Hydraulics 3D-SEDiment; Spasojevic and Holly (1994)	—	Unsteady	Yes	Yes	Yes	Yes	Entrainment and deposition	C	C	F90
SSIIM: Sediment Simulation In Intakes with Multiblock options; Olsen (1994)	V. 2.0 (2006)	Steady	Yes	Yes	Yes	No	Advection-diffusion	PD	P	C-Langua.
MIKE 3: Danish acronym of the word Microcomputer; Jacobsen and Rasmussen (1997)	—	Unsteady	[a]Yes	[a]Yes	No	Yes	Entrainment and deposition	C	P	F90
FAST3D: Flow Analysis Simulation Tool; Landsberg et al. (1998)	V. Beta-1.1 (1998)	Unsteady	Yes	Yes	No	No	Entrainment and deposition	LD	P	F90
Delft 3D; Delft Hydraulics (1999)	V. 3.25.00 (2005)	Unsteady	Yes	Yes	No	Yes	Entrainment and deposition	C	LD	F77
TELEMAC; Hervouet and Bates (2000)	—	Unsteady	[a]Yes	[a]Yes	No	Yes	Entrainment and deposition	C	P	F90
Zeng et al. (2005)	—	Unsteady	Yes	Yes	No	No	Entrainment and deposition	P	P	F90

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[a]Treated as a total load without separation.

lating sediment transport and associated bed level change under conditions of combined quasi-steady currents and wind-induced waves over a sediment bed. The model solves the general advection-diffusion equations by incorporating a lag coefficient to account for the settling of sediments.

TABS-2: A group of finite-element based hydrodynamic and sediment transport computer codes developed by the USACE Waterways Experimental Station (Thomas and McAnally 1985) that currently operates by using the SMS v.9.0 windows interface. These codes are applicable to rivers, reservoirs, and estuaries. The main components of TABS-2 are the hydrodynamic component, RMA2; the sediment transport component, SED2D (formally STUDH); and the water quality component, RMA4.

MOBED2: A finite-difference hydrodynamic and sediment transport model used in a curvilinear coordinate system, developed by Spasojevic and Holly (1990a). The model can simulate water flow, sediment transport, and bed evolution in natural waterways such as reservoirs, estuaries, and coastal environments where depth averaging is appropriate.

ADCIRC-2D: A finite-element hydrodynamic and sediment transport model developed by Luettich et al. (1992) in a rectilinear coordinate system for simulating large-scale domains (e.g., the entire East Coast of the United States) by using 2D equations for the "external mode" but using the "internal mode" for obtaining detailed velocity and stress at localized areas. The internal mode is achieved by specifying the momentum dispersion and the bottom shear stress in terms of the vertical velocity profile. The wave-continuity formulation of the shallow-water equations is used to solve the time-dependent, free-surface circulation and transport processes.

MIKE2: A finite-difference model in a rectilinear coordinate system developed by the Danish Hydraulic Institute (1993) for simulating transport and fate of dissolved and suspended loads discharged or accidentally spilled in lakes, estuaries, coastal areas, or in the open sea. The system consists of four main model groups (modules), namely, the hydrodynamic and wave models, the sediment process model, and the environmental hydrodynamic model groups. The hydrodynamic and wave models are relevant to the types of physical processes considered in floodplain mapping. The sediment process models are used to simulate shoreline change and sand transport, whereas the environmental hydrodynamic models are used to examine water quality issues.

UNIBEST-TC2: A finite-difference hydrodynamic and sediment transport model in a rectilinear coordinate system to describe the hydrodynamic processes of waves and currents in the cross-shore direction by assuming the presence of uniform mean

Table 4. Applications for Selected 1D Models

Model and references	Applications
HEC-6; Thomas and Prashum (1977)	Prediction of the flow and sediment transport along with the bed level change of the Saskatchewan River below Gardiner Dam, Canada (Krishnappan 1985)
	Prediction of the bed profile for the eroded and redeposited delta sediment upstream from Glines Canyon Dam, Washington (U.S. Department of Interior, Bureau of Reclamation 1996)
MOBED; Krishnappan (1981)	Comparison of MOBED results with HEC-6 results for the flow and sediment transport along with the bed-level change for the Saskatchewan River below Gardiner Dam, Canada (Krishnappan 1985)
	Prediction of fine sediment transport under ice cover in the Hay River in Northwest Territories, Canada
IALLUVIAL; Karim and Kennedy (1982)	Simulation of flow and sediment processes in the Missouri River, Nebraska (Karim and Kennedy 1982)
	Simulation of flow and sediment processes downstream of the Gavins Point Dam on the Missouri River, Nebraska (Karim 1985)
FLUVIAL 11; Chang (1984)	Simulation of flow and sediment processes of the San Dieguito River, Southern California (Chang 1984)
	Simulation of flow and sediment processes of the San Lorenzo River, Northern California (Chang 1985)
GSTARS; Molinas and Yang (1986)	Prediction of the scour depth and pattern at the Lock and Dam No. 26 replacement site on the Mississippi River, Illinois (Yang et al. 1989)
	Prediction of the variation in channel geometry for the unlined spillway downstream Lake Mescalero Reservoir, New Mexico (Yang and Simões 2000)
CHARIMA; Holly et al. (1990)	Mobile-bed dynamics in the Missouri River from Ft. Randall to Gavins Point Dam, South Dakota (Corps of Engineers)
	Mobile-bed dynamics in the Missouri River from Gavins Point Dam to Rulo, Nebraska (National Science Foundation)
SEDICOUP; Holly and Rahuel (1990)	Modeling of long-term effects of rehabilitation measures on bed-load transport at the Lower Salzach River, Germany (Otto 1999)
	Long-term modeling of the morphology of the Danube River, Germany (Belleudy 1992)
OTIS; Runkel and Broshears (1991)	Simulation of field experiments conducted by Bencala and Walters (1983) for the change in chloride concentration of the Uvas Creek, California.
	Estimation of the travel times and mixing characteristics of the Clackamas River, Oregon, using the slug of rhodamine data of Laenen and Risley (1997)
EFDC1D; Hamrick (2001)	Simulation of the flow and sediment transport processes in the Duwamish River and Elliott Bay, Washington (Schock et al. 1998)
	Development of a water quality model for the Christina River, Delaware (USEPA 2000)
3STD1; Papanicolaou et al. (2004)	Prediction of the grain size distribution and bed morphology of the Cocorotico River, Venezuela (Papanicolaou et al. 2004).
	Prediction of the grain size distribution and bed-load rate of the Alec River, Alaska (Papanicolaou et al. 2006)

longshore currents along the beach (Bosboom et al. 1997). The bed load and suspended load transport processes are modeled by assuming local equilibrium conditions (no lag effects are considered between flow and sediment).

USTARS: A modified form of (GSTARS) that is also based on the stream tube concept (Lee et al. 1997). The hydrodynamic and sediment equations are solved with a finite-difference scheme in a rectilinear coordinate system. As in GSTARS, the theory of minimum stream power is used here to determine the optimum channel width and geometry for a given set of hydraulic, geomorphologic, sediment, and man-made constraints.

FAST2D: A finite-volume hydrodynamic and sediment model with boundary-fitted grids in a curvilinear coordinate system to simulate sediment transport and morphodynamic problems in alluvial channels (Minh Duc et al. 1998). The model accounts indirectly for secondary effects attributed to the complexity of the domain.

FLUVIAL 12: A finite-difference hydrodynamic and sediment model in a curvilinear coordinate system developed by Chang (1998). The combined effects of flow hydraulics, sediment transport, and river channel changes can be simulated for a given flow period. The model is a mobile-bed model and simulates changes in the channel-bed profile, width, and sediment bed composition induced by the channel curvature.

DELFT-2D: A finite-difference hydrodynamic and sediment transport model simulating waves and currents (Walstra et al. 1998). The model couples the hydrodynamics with computed bottom morphological changes in a time-dependent way. The model can simulate bed-load and suspended load transport by using either a local equilibrium or a nonequilibrium (i.e., the lag effects between flow and sediment) approach. The model can also show the effects of wave motion on transport magnitude and direction.

CCHE2D: A finite-element hydrodynamic and sediment model developed by Jia and Wang (1999). The model simulates the suspended sediment by solving the advection-diffusion equation and the bed-load transport by empirical functions (e.g., Yalin 1972; van Rijn 1993). The model accounts for the secondary flow effect in curved channels.

All the aforementioned models are applicable to unsteady flow conditions, except SUTRENCH-2D by van Rijn and Tan (1985) and UNIBEST-TC2 by Bosboom et al. (1997). All models can predict the total sediment transport load; but only MOBED2, USTARS, FLUVIAL 12, and CCHE2D can handle multifractional sediment transport and can decompose the total sediment load into bedload and suspended load. DELFT-2D and FAST2D can also separate the total sediment load into bedload and sus-

Table 5. Applications for Selected 2D Models

Model and references	Applications
SERATRA; Onishi and Wise (1982)	Investigation of the effects of sediment on the transport of radionuclides in Cattaraugus and Buttermilk Creeks, New York (Walters et al. 1982)
	Simulation of the hydrogeochemical behavior of radionuclides released to the Pripyat and Dnieper rivers from the Chernobyl Nuclear Power Plant in Ukraine (Voitsekhovitch et al. 1994)
SUTRENCH-2D; van Rijn and Tan (1985)	Simulation of sand transport processes and associated bed-level changes along dredged pits and trenches at the lower Dutch coast, The Netherlands (Walstra et al. 1998)
	Modeling sediment transport and coastline development along the Iranian coast, Caspian Sea (Niyyati and Maraghei 2002)
TABS-2; Thomas and McAnally (1985)	Simulation of the flow and sediment transport processes in the Black Lake, Alaska (Papanicolaou et al. 2006)
	Evaluation of the hydraulic performance of different structures found in the Missouri River for creating new shallow water habitat (Papanicolaou and Elhakeem 2006)
MOBED2; Spasojevic and Holly (1990a)	Simulation of mobile-bed dynamics in the Coralville Reservoir on the Iowa River, Iowa (Spasojevic and Holly 1990b)
ADCIRC; Luettich et al. (1992)	Simulation of the flow and sediment transport processes of the natural cap in the Matagorda Bay, Texas (Edge 2004)
	Simulation of sand transport processes at Scheveningen Trial Trench, The Netherlands (Edge 2004)
MIKE 21; Danish Hydraulic Institute (1993)	Prediction of the spreading of dredged spoils in the Øresund Link, Denmark-Sweden
	Prediction of sediment transport rate at ebb flow in a tidal inlet, Grådyb, Denmark
UNIBEST- TC; Bosboom et al. (1997)	Coastal study for the impacts of constructing Kelantan Harbor, Malaysia
	Coastal study for shoreline protection of Texel region, The Netherlands
USTARS; Lee et al. (1997)	Simulation of sand transport processes and associated bed-level changes of a reach in the Keelung River, Taiwan (Lee et al. 1997)
	Routing of flow and sediment of the Shiemen Reservoir, upstream Tan-Hsui River, Taiwan (Lee et al.1997)
FAST2D; Minh Duc et al. (1998)	Simulation of sediment transport processes and associated bed level changes of a reach in the Bavarian Danube River, Germany (Minh Duc et al. 1998)
	Flood analysis and mitigation on the Orlice River, Poland (Beck et al. 2003)
FLUVIAL 12; Chang (1998)	Simulation of flow and sediment processes of the San Dieguito River, Southern California (Chang 1994)
	Simulation of flow and sediment processes of the Feather River, Northern California (Chang et al. 1996)
Delft 2D; Walstra et al. (1998)	Simulation of sand transport processes and associated bed-level changes along dredged pits and trenches at the lower Dutch coast, The Netherlands (Walstra et al. 1998)
	Simulation of the flow field and sediment transport processes of the Pannerdense Kop and IJssel Kop bifurcations in the Rhine River, The Netherlands (Sloff 2004)
CCHE2D; Jia and Wang (1999)	Investigation of the effects of the rock pile and the submerged dikes downstream of the Lock and Dam No. 2 of the Red River Waterway, Louisiana
	Investigation of the effects of large woody debris structures on the fluvial processes in the Little Topashaw Creek, Mississippi (Wu et al. 2005)

pended load, but they are limited to uniform sediment sizes. Examples of the different 2D model applications are summarized in Table 5.

Three-Dimensional Models

In many hydraulic engineering applications, one has to resort to 3D models when 2D models are not suitable for describing certain hydrodynamic/sediment transport processes. Flows in the vicinity of piers and near hydraulic structures are examples in which 3D flow structures are ubiquitous and in which 2D models do not adequately represent the physics. With the latest developments in computing technology—such as computational speed, parallel computing, and data storage classification—3D hydrodynamic/sediment transport models have become much more attractive to use. Most 3D models solve the continuity and the Navier-Stokes equations, along with the sediment mass balance equation through the methods of finite difference, finite element, or finite-volume. The Reynolds average Navier-Stokes (RANS) approach has been employed to solve the governing equations.

The RANS models can be separated into hydrostatic and nonhydrostatic models. The hydrostatic models (e.g., Gessler et al. 1999) are not able to accurately predict flow and transport phenomena in regions where the flow is strongly 3D and where large adverse pressure gradients or massive separation are present (e.g., river bends containing hydraulic structures). On the contrary, nonhydrostatic RANS models have been shown to adequately describe intricate features of secondary flows in complex domains (e.g., Wu et al. 2000; Ruther and Olsen 2005).

Table 3 shows the complete model reference and explanation of the acronym and summarizes the characteristics of 12 selected 3D hydrodynamic/sediment transport models. The main specific features of each model are described below:

ECOMSED: A fully integrated 3D finite-difference hydrodynamic, wave, and sediment transport model in an orthogonal cur-

Table 6. Applications for Selected 3D Models

Model and references	Applications
ECOMSED; Blumberg and Mellor (1987)	Simulation of the flow and sediment transport processes of Lavaca Bay, Texas (HydroQual 1998)
	Simulation of the flow and sediment transport processes of the Klarälven River east and west channels at the bifurcation, Sweden (Admass 2005)
RMA-10; King (1988)	Modeling of the Nisqually River Delta to evaluate habitat restoration alternatives, Washington
	Modeling the hydrodynamics of flow and sediment of the Los Angeles and Long Beach harbors California (Tetra Tech 2004)
GBTOXe; Bierman et al. (1992)	Simulation of fate and transport of PCBs in Green Bay, Wisconsin
EFDC3D; Hamrick (1992)	Modeling of the hydrodynamic and sediment processes in Moro Bay, California
	Simulation of flow and sediment transport of Lake Hartwell reservoir on the Savannah River between South Carolina and Georgia
ROMS; Song and Haidvogel (1994)	Modeling of sediment transport and estuary turbidity maximum of the Hudson River Estuary, New York
	Simulation of flow and sediment quality of the Southern California Bight, California
CH3D-SED, Spasojevic and Holly (1994)	Evaluation of the relative impact of different sediment sources on the shore areas of the western basin of Lake Erie, Ohio (Velissariou et al. 1999)
	Simulation of sedimentation on bends, crossings, and distributaries on the lower Mississippi River and Atchafalaya River, Lousiana
SSIIM; Olsen (1994)	Tested against experimental data from Colorado State University (Olsen 2003)
MIKE 3; Jacobsen and Rasmussen (1997)	Simulation of the flow, sediment transport processes, and water quality of Upper Klamath Lake, Oregon
	Simulation of the flow, sediment transport processes, and water quality of Tampa Bay, Florida
FAST3D; Landsberg et al. (1998)	Tested against the experimental data of Odgaard and Bergs (1988)
	Simulation of contaminated regions resulting from hypothetical airborne agent releases in major urban areas at Washington D.C., Maryland, and Chicago, Illinois (Pullenet al. 2005)
Delft 3D; Delft Hydraulics (1999)	Simulation of the flow, sediment transport processes and water quality of Tolo Harbor and Mirs Bay, Hong Kong (Delft Hydraulics 1999)
	Morphodynamic modeling of the German Wadden Sea and Duck, North Carolina (Delft Hydraulics 1999)
TELEMAC; Hervouet and Bates (2000)	Development of a mesoscale hydrodynamic and sediment transport model for the Peru Basin in the Southeast Pacific Ocean (Zielke et al. 1995)
	Simulation of transport and Fate of Toxic Chemicals in Shasta Reservoir, California (Gu and Chung 2003)
Zeng et al. (2005)	Tested against the experimental data of Odgaard and Bergs (1988)

vilinear coordinate system developed by Blumberg and Mellor (1987). The model uses the hydrostatic pressure distribution assumption and can predict fate and transport processes in large water bodies such as lakes and oceans.

RMA10: A finite-element hydrodynamic model for computing water-surface elevations and horizontal velocity components for stratified free-surface flow (King 1988). It is designed for water bodies in which vertical accelerations can be considered negligible (hydrostatic pressure assumption is considered). The model solves the transport equation for salinity, temperature, and suspended sediment and incorporates the effect of these quantities on density. The model is suited for computing the hydrodynamics in tidal flats and wetlands. The model is limited to uniform sediment. RMA10 is a component of TABS-MD (multi-dimensional).

GBTOXe: A finite-difference model that is formulated in a rectilinear coordinate system and is developed for predicting transport and fate of PCBs in riverine environments. The model was originally developed for addressing the fate and transport issues of PCBs in Green Bay, Wisconsin (Bierman et al. 1992). The hydrodynamic component of the model (GBHYDRO) assumes hydrostatic pressure and accounts for water column circulation and mixing processes, whereas the sediment transport component (GBSED) accounts for the transport of cohesive sediment.

EFDC3D: A finite-difference hydrodynamic and water-quality constituent transport model in an orthogonal curvilinear or rectilinear coordinate system with a sigma or stretched approximation in the vertical direction (Hamrick 1992). The model solves the 3D, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable density fluid. The model can simulate complex water bodies, such as vertically mixed shallow estuaries, lakes, and coastal areas. The model has also capabilities to predict toxic contaminants and water quality state variables. Currently, there is an effort to incorporate the EFDC3D code into BASINS, an EPA open-source watershed model that links terrestrial (i.e., uplands) and in-stream models.

ROMS: A finite-difference model in an orthogonal curvilinear coordinate system with sigma-stretched approximation in the vertical direction (Song and Haidvogel 1994). The model can simulate free-surface hydrostatic ocean circulation and parameterizes the effect of surface waves on bottom stresses and apparent roughness.

CH3D-SED: A boundary-fitted finite-difference model in the nonorthogonal coordinate system with a sigma-stretched approximation in the vertical direction (Spasojevic and Holly 1994). The sedimentation component is based on solving the sediment mass balance equation for bedload along with the advection-diffusion equation for suspended load transport.

SSIIM: A finite volume hydrodynamic and sediment transport model that is based on an unstructured grid system (Olsen 1994). The model has the capability of simulating sediment transport in a movable riverbed with complex geometries. It includes the modeling of meandering and bed forms in rivers and bed load and suspended load transport of nonuniform sediment and associated sorting and armoring processes. The model has been extended to such other hydraulic engineering applications as spillway modeling, head loss in tunnels, meandering in rivers, and turbidity currents. The model has also been used for water quality and habitat studies in rivers.

MIKE3: A finite-difference model in an orthogonal grid system developed by the Danish Hydraulic Institute (1993) for free surface flows. It includes modeling components for advection-diffusion, water quality, heat exchange with the atmosphere, heavy metals, eutrophication, flooding and drying of intertidal areas, and sediment processes (Jacobsen and Rasmussen 1997). The model can simulate the fate and transport of conservative or linearly decaying constituents, including such processes as nutrient cycling; dissolved oxygen levels; exchange of metals between the bed sediments and the water column; and sediment transport, deposition, and entrainment.

FAST3D: A fully nonhydrostatic 3D finite-volume hydrodynamic model (Landsberg et al. 1998). The underlying fluid dynamics algorithm used in FAST3D is the flux-corrected transport (FCT), a high-order–high-resolution algorithm. The model can handle complex geometric domains mainly because of the added capabilities that are provided by an efficient parallel implementation of the virtual cell embedding (VCE) algorithms. The sediment component of the model accounts for nonequilibrium bed-load rate and advection-diffusion–based suspended load rate (Wu et al. 2000). A hydrogen-oxygen induction parameter (reduced chemistry) model is also included in FAST3D. This model allows multiple chemical species sharing a single velocity field.

DELFT3D: An integrated modeling system developed by the Delft Hydraulic Laboratory team that is solved through the finite-difference scheme (Delft Hydraulics 1999). The modeling system contains several submodels that simulate the temporal and spatial variation of six processes (flow, waves, water quality, morphology, sediment transport, and ecology). The hydrodynamic submodel calculates nonsteady flow resulting from tidal and meteorological forcing on a boundary-fitted curvilinear grid system.

TELEMAC-3D: A finite-element hydrodynamic and transport model for free-surface boundary condition to characterize the fate and transport in coastal zones (Hervouet and Bates 2000). For the water quality component, the model solves the advection-diffusion equation with additional terms to account for transient storage, lateral inflow, first-order decay, and sorption.

Zeng et al. (2005) model: A nonhydrostatic fully 3D model in generalized curvilinear coordinates that is solved through the finite-difference scheme. The model solves the governing equations by integrating them up to the near-wall boundary to avoid any near-wall approximations. The solver uses movable grids in the vertical direction to account for changes in the free-surface elevation. The proper kinematic and dynamic conditions are imposed to account for changes in the bathymetry because of erosion or deposition at the bed. The suspended sediment is modeled by using an advection-diffusion equation with a settling velocity term.

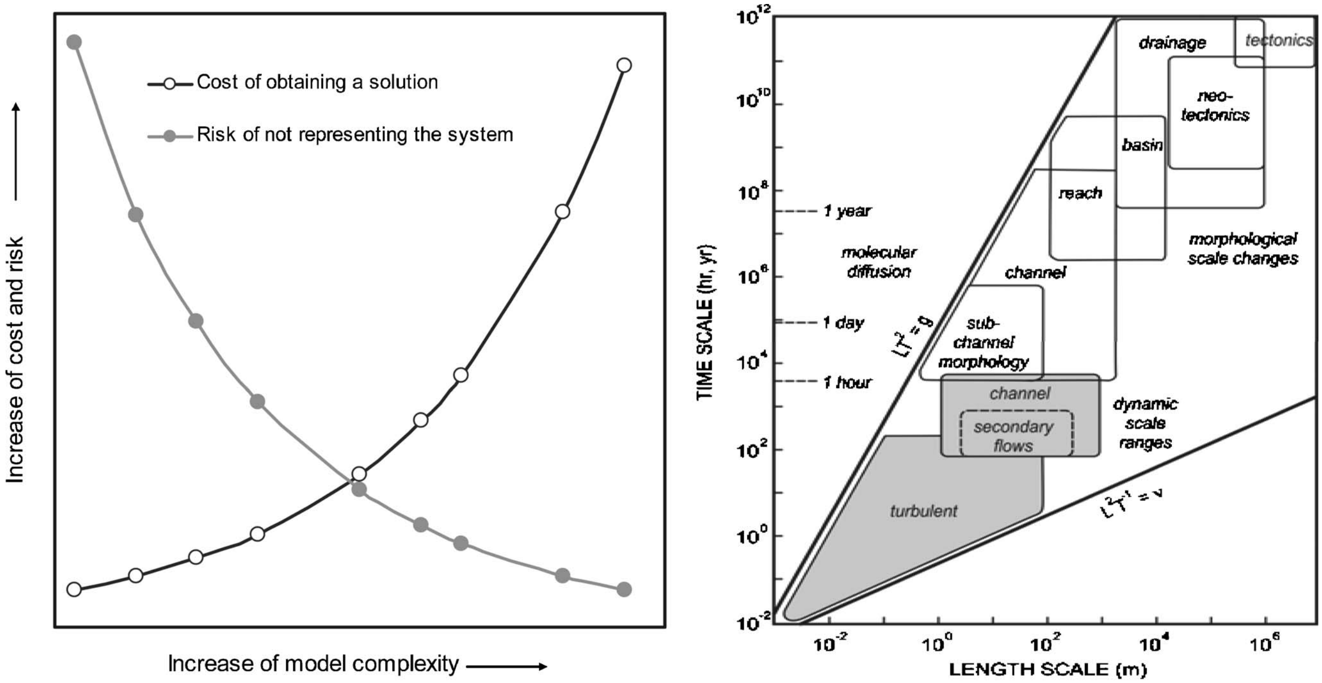
Except for the SSIIM model by Olsen (1994), all the aforementioned models are applicable to unsteady flow conditions. Except GBTOXe by Bierman et al. (1992), all of them can predict the total sediment load. Only EFDC3D by Hamrick (1992), ROMS by Song and Haidvogel (1994), CH3D-SED by Spasojevic and Holly (1994), and SSIIM by Olsen (1994) have the capabilities to predict the gradation of sediment mixtures; whereas the other models are applicable to uniform sediment only. ECOMSED by Blumberg and Mellor (1987), RMA10 by King (1988), MIKE3 by the Danish Hydraulic Institute (1993), and TELEMAC-3D by Hervouet and Bates (2000) cannot separate the total sediment load into bedload and suspended load. A few examples of the different 3D model applications are summarized in Table 6.

Discussion and Future Research

Discrepancies between hydrodynamic/sediment transport model predictions and measurements can be attributed to different causes. They include oversimplification of the problem by using an inappropriate model (1D versus 2D or 2D versus 3D), the use of inappropriate input data, lack of appropriate data for model calibration, unfamiliarity with the limitations of the hydrodynamic/sediment transport equations used in developing the model, and computational errors in source codes because of approximations in the numerical schemes used in solving the governing equations (boundary condition problems/truncation errors because of discretization). The last reason is beyond the scope of this forum article, and techniques needed to minimize these computational errors can be found in computational fluid dynamics textbooks (e.g., Chaudhry 1993; Anderson 1995; Tannehill et al. 1997). However, both hydrodynamic and sediment equations will include such computational errors.

In many applications, inherent model limitations do not allow accurate simulation of a process independently of data input and model calibration. An explanation for this is that the eddy viscosity models that are frequently used in solving the governing hydrodynamic equations of turbulent flows include some degree of empiricism in their formulations. The problem is compounded for sediment transport models, which rely heavily on experimental and field information and whose formulations involve a high degree of empiricism. As a consequence, at the present stage, no reliable and comprehensive theoretical formulas can describe the two-phase phenomenon of sediment and flow.

It is not surprising, therefore, that Dawdy and Vanoni (1986) in their examination of some of the available 1D hydrodynamic/sediment transport models concluded that most of the movable bed models were found not to yield wholly satisfactory results. This study concluded that most of the 1D models assume that a stage of equilibrium exists with respect to sediment transport and that the nature of sediment entrainment is deterministic and not a stochastic process. However, 2D and 3D hydrodynamic/sediment transport models typically encounter problems in determining the reference concentration of sediment near the bed and simulating the term for sediment diffusion because of turbulent motion. Also, the users of the multidimensional models experience difficulties in determining the source term of the advection-diffusion equation and the effects of sediment motion on near-bed turbulent flow characteristics.



a) The model complexity trade-off diagram (adapted by Overton and Meadows 1976).

b) Illustration of spatial and temporal scales (adapted by Church 2006)

Fig. 1. Factors governing model choice: (a) the model complexity trade-off diagram (adapted from Overton and Meadows 1976); (b) illustration of spatial and temporal scales (adapted from Church 2006)

In subsequent sections, the authors will attempt to provide an insight for model users about model choice and also highlight the future research needs for improving available hydrodynamic/sediment transport models.

Model Choice

It should be accepted that sediment transport models incorporate a certain degree of simplification to be computationally feasible. Simplified models run into the risk of not obtaining a reliable solution, whereas increasing the model complexity can complicate the problem formulation and incur more input data preparation, calibration, and verification costs. Such a trade-off between complexity and cost [Fig. 1(a)] has been discussed by Overton and Meadows (1976) and Simons and Simons (1996). One practical question that model users typically face is the choice of the appropriate dimensional model. Although a definitive answer to this question does not exist, users need to follow some rules of thumb. In general, a model should be chosen in the way that the model hydrodynamic/sediment components retain all relevant terms related to a specific problem. In addition, Fig. 1(b) gives a guideline for simulating processes of different spatial and temporal scales (Church 2006). As Fig. 1(b) shows, a direct correspondence exists between the time scale and the length scale. Morphologic scale changes at the basin or catchment scale (length scale greater than 10^4 m) typically occur in a 1-year period or greater. As a consequence, a 1D or 2D model may be sufficient to simulate these changes. Dynamic scale processes, however, occur at smaller length scales such as channel reach and sediment particle scale. A reference time scale for these processes ranges from seconds to an hour. Figure 1(b) implies that, for simulation of flow at the reach scale or around an obstacle, the role of turbulence is important. As a result, 3D models should be used to simulate flow in smaller scales where detailed mapping of the turbulent microstructure is required. This finding goes hand in hand with the realization that the use of 3D models to simulate basin-scale processes may not be realistic because it currently is a very costly endeavor at the present.

Model Input and Calibration

Model input and calibration give rise to new demands on field data. The following question arises: Do these data exist, or can they be collected within the constraints of time and money? Although this question is a pragmatic one, the following discussion may aid in an appropriate response. Transport of sediment is one of the most important and difficult classes of processes encountered by the hydraulic engineer. Despite the importance of the subject, it is probable that a greater differential exists between the information needed and the information available than in almost any other practical engineering hydraulic field. Traditional measurement protocols of bed bathymetry, stages, grain size distribution, bed morphology and velocity, and shear stress distributions using point or cross-sectional measurements are applicable to a limited spatial and temporal resolution and hinder adequate model calibration and verification. For example, point or cross-sectional measurements in a riverine environment with mobile bed, obtained through acoustic Doppler velocimeter (ADV) or acoustic Doppler current profiler (ADCP), may not be sufficient for model calibration and verification because the flow distribution at a cross section changes in time because of bed-form propagation. Also, calibration of mobile bed models on the basis of limited spatial data can be questionable, especially in a dynamic mobile environment. Thus far, traditional measurement protocols are adequate under conditions that are closely represented by static conditions. The recent boom in sensor technology for in-stream flow and sediment measurements, however, may alleviate some of the limitations regarding model data input, construction, calibration, and verification.

The absence of a symbiotic relationship between measurements and simulation is another important factor that needs further investigation and relates to model calibration, verification, and grid refinement. The novel capabilities to be sought in the future are applications of simulations that can dynamically accept responses to on-line field data and measurements and/or control such measurements. This synergistic and symbiotic feedback control loop between simulation and measurements is a novel technical direction that can open domains in the capabilities of simulations within riverine/estuarine environments and facilitate capturing episodic and catastrophic events. This control loop is not currently available for simulating natural flows because of the limited data that can be obtained from traditional measurement protocols. As a result, many simulations work in the batch mode; an event is simulated on the basis of a static set of field data. For example, hydrodynamic/sediment transport models to predict morphodynamic changes within streams and the impact of these changes on aquatic life are conducted by considering a constant sediment input value from such terrestrial inputs as roads, flood plains, and other disturbance references. Hence, perturbations that exist in the system because of spatial and temporal variability in the terrestrial environment are not accounted for. The recent boom in sensor technology can fill the gap between simulation and measurement needs. However, the riverine/estuarine community has to adopt the symbiotic existence of sensors and models to ensure adequate model calibration and verification. Then and only then can the calibration and verification of models, occurring in a dynamic fashion, be fully realized.

Another issue that closely relates to the symbiotic relationship between mobile bed models and sensors is the issue of grid refinement and grid sensitivity. Several questions may be raised. For example, are grid-independent tests necessary and practical? Can a coarse grid lead to misleading results? What is the optimum grid size for capturing turbulence-resolving scales? These questions have no universal answers. Different grid refinement criteria to simulate flow and sediment dynamics may produce equally viable mobile bed responses for a given problem. Ultimately, one must rely on the known notion of good engineering judgment.

Since the early 1980s, 1D models have been used heavily for simulating large spatial scales (covering the order of 100s of kms) over a long period of time (of the order of decades). However, developments in computer capabilities have recently advanced the use of 2D and 3D models in natural environments for simulating flow/sediment transport processes and fate of their associated pollutants. Improved computing facilities significantly reduce computational requirements and at the same time allow better grid refinement. As the discipline of computational fluid and mobile bed dynamics evolves at a time when computational and sensor technologies are drastically improving, it is imperative that all of us prepare the ground for incorporating multidimensional models into engineering practice. Undoubtedly, multidimensional—and especially 3D—models move closely approximate the complex processes occurring in waterways, and it is anticipated that they will become the models of the near future.

Model Limitations

It has been pointed out that a mismatch exists in the theoretical foundations and performance of the hydrodynamic and sediment components of models. The disparity that exists between the hydrodynamic and sediment transport components is attributed to the fact that the principles of hydrodynamics and the fundamentals of turbulence theory and modeling have been established over the previous two decades, as compared with the fundamentals of sediment transport (e.g., Tannehill et al. 1997; Raudkivi 1998; Parker et al. 2000; Rodi 2006). Modeling of turbulence is probably the weakest component in the hydrodynamic equations of flow. Although the RANS models are computationally effective, as all turbulent fluctuations are averaged out from the equations solved, they are criticized as "postdiction" rather than "prediction" because of the loss of information occurring from averaging the equations.

Both DNS and LES are principally better suited for simulating complex turbulent flows. DNS requires enormous computing resources and thus is not a method that can be used for an everyday engineering problem (Rodi 2006). DNS can be a valuable research resource for studying the transition between laminar and turbulent flow, considering that this method is limited to low Reynolds numbers.

On the contrary, LES can be used at low and high Reynolds numbers. At high Reynolds numbers, LES can capture the larger-scale turbulent structures (eddies) on a given grid by employing the 3D unsteady Navier-Stokes equations. The smaller-scale coherent structures that are believed to control the momentum and mass exchange directed from and to the riverbed cannot be resolved directly with LES, and special near-wall treatment has to be introduced to account for the smaller-scale structures. Despite the limitations that LES may have especially for high Reynolds numbers, LES is the most advanced modeling tool currently available for modeling 3D complex flows (Mahesh et al. 2004). Nevertheless, advances made in the DNS and LES arena allow the realistic prediction of complex turbulent flows around structures such as flow in fish ladders of hydroelectric dams, flow around groynes, and flow around bridge structures (e.g., Lai et al. 2003).

Simulation of the sediment transport processes remains open to future research because sediment transport is not only controlled by randomness in flow but also by irregularities in landform and bed surface geometry (e.g., Nino and Garcia 1996; Papanicolaou et al. 1999). On account of these factors, the sediment transport models developed thus far are not as universal as a hydraulic engineer would like them to be. Some of the limitations that most sediment transport models exhibit can be summarized as follows:

One assumption is that sediment entrainment is not triggered by the near bed flow turbulent characteristics but by the excess shear stress term ($\tau - \tau_c$). In most entrainment formulas, shear stress τ is determined by assuming uniform flow conditions (e.g., Gomez and Church 1989; Almadeij and Diplas 2005). Recent studies have shown that turbulent sweeps, outward interactions, and ejections are the primary triggering mechanisms of sediment entrainment (Papanicolaou et al. 2001).

The traditional approach in sediment transport models (e.g., excess shear stress models; settling velocity models) has been to calculate the transport rate by using a single characteristic grain size, such as the median (Raudkivi 1998). Because this approach does not account for differential transport of sediment particles with different size (or density), it is likely to underpredict or overpredict the transport rate of individual fractions when bimodal or multimodal distributions are present atop the surface bed (e.g., Holly and Usseglio-Polatera 1984; Usseglio-Polatera and Cunge 1985; Pavlovic et al. 1985). Furthermore, most multidimensional models treat flow and sediment processes as entirely uncoupled or semicoupled within one computational time step (or even during a sequence of time steps in some cases), so that the influence of changes in bed elevation and surface bed material size distribution on the flow field can be taken into account only approximately (e.g., Thomas and McAnally 1985; Onishi and Trent 1985).

Recognition of the fact that a sediment particle of an certain size or density can be transported at different rates has led to the development of formulations that predict multifractional transport rates (Raudkivi 1998). Expressions developed for the traveling velocity of particles (e.g., Sekine and Kikkawa 1992; Jain 1992; Papanicolaou et al. 2002; Ferguson et al. 2002; Parker et al. 2003; Francalanci and Solari 2007) provide the resting and moving periods of particles of different sizes and the lag coefficient for the movement of different sediment fractions. These formulations allow different sizes to move at different rates, and their inclusion into future sediment transport modeling can perhaps improve the predictive ability of these models.

The treatment of the dispersion and diffusion coefficients as functions of the inner and outer variables, respectively, namely, the friction velocity, depth-averaged velocity, width of channel, and mean flow depth is limited. It has been shown that the spatially averaged inner and outer quantities may not be good approximations of the dispersion process in channel constrictions or expansions and flows near submerged or unsubmerged obstacles (hydraulic structures). Furthermore, the role of relative submergence on the estimation of the dispersion coefficient has not been assessed (Tayfur and Singh 2005).

In most cases, the source term in the advection-diffusion equation does not account for the soil contributions from the bank or the terrestrial contributions from the hill slopes and floodplains (Toda et al. 2005). Attempts to connect sediment sources originating from the hill slopes and floodplains with in-stream processes are of paramount importance for minimizing error in the predictive ability of existing sediment transport models. The studies of Collins et al. (1998), Fox et al. (2005a,b), Toda et al. (2005), and others reveal that new technologies—such as Lidar, biogeochemical tracers, and remote sensing—need to be employed to address the connectivity between hill slopes and floodplains and instream processes.

The formulation of the sediment-flow interaction processes needs further investigation (Lyn 1992). Recent attempts to formulate general mathematical models of sediment-flow interaction have been inspired by the progress made in two-phase flow modeling in other fields (e.g., Ishii 1975; Drew 1983; Elghobashi 1994; Crowe et al. 1996). The basic idea behind the two-phase flow approach (e.g., Villaret and Davies 1995; Ni et al. 1996; Cao et al. 1995; Greimann et al. 1999) is to formulate governing conservation equations for both phases, which include terms defining interaction between phases, such as the stress tensor attributable to phase interactions or the interfacial momentum transfer term.

However, even though the two-phase flow approach seems promising, its use and even the formulation of the governing equations in flow-sediment problems are still in their infancy. Certain terms in the governing equations that are typically neglected in other fields may require quite a different treatment in the flow-sediment field. The stress between fluid and sediment particles is usually neglected under the assumption that it is much smaller than the turbulent stress between fluid particles. The stress coming from interactions among sediment particles is neglected under the assumption that sediment particles do not contact one another. Both of these assumptions are questionable in the case of high sediment concentrations, especially near the bed. This probably explains a lingering doubt about the use of the two-phase flow approach in the near-bed areas. Furthermore, certain terms in the two-phase flow governing equations, such as the interfacial momentum transfer, require additional modeling to achieve system closure. Such modeling has to be based on a detailed knowledge of turbulence and requires presently unavailable experimental data. Finally, the two-phase flow solution of practical sediment problems, which routinely requires long-term simulations, is likely to be CPU-time-prohibitive even in the not-so-near future.

In parallel with the research in sediment transport, new modeling paradigms such as artificial neural networks fuzzy logic, and other related methods have emerged (Bhattacharya et al. 2007). These methods offer an alternative to traditional sediment transport modeling, especially in cases where too little data are available for calibrating traditional sediment transport models.

Future research should not only focus on the previously stated limitations but also on other cross-cutting issues such as reconciling different spatial and temporal scales and the capability of dynamically simulating bed evolution and sediment exchange processes between the sediment bed and the water column. Also, further investigation is required on the role of grid refinement and grid sensitivity and the required amount of data for mobile bed model calibration and verification.

Acknowledgments

The writers would like to acknowledge the following individuals for the guidance, input and assistance that they have provided: Professor Forrest Holly from the University of Iowa; Professor Rick Luettich from the University of North Carolina; Professor Wolfgang Rodi from the University of Karlsruhe; Professors Leo van Rijn and Dirk-Jan Walstra from WL/Delft Hydraulics; Professor Nils Olsen from the Norwegian University of Science and Technology; Dr. Bommanna Krishnappan from the Aquatic Ecosystem Impacts Research Branch; Pierre Lang from Sogreah/LHF; Charles Kirsty, Patrick Delaney, and Karen Edelvang from the DHI, Inc. support team; and the ECOMSED support team.

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