Environmental Fluid Dynamics Code (EFDC)
EFDC+ Version

Model Description

1 Introduction

The Environmental Fluid Dynamics Code (EFDC) is a general-purpose modeling package for simulating three dimensional (3-D) flow, transport, and biogeochemical processes in surface water systems including: rivers, lakes, estuaries, reservoirs, wetlands, and near-shore to shelf-scale coastal regions. The EFDC model was originally developed at the Virginia Institute of Marine Science (Hamrick, 1992) for estuarine and coastal applications and is public domain software. Beginning in 1998, Dynamic Solutions-International, LLC (DSI) has taken the code and continued to develop its capabilities and improve model performance. DSI has collaborated with several other organizations include the Environmental Protection Agency (EPA), Sandia National Laboratory (SNL) and the U.S. Army Corp of Engineers (USACE) to include capabilities developed in the open source environment. DSI has integrated these updates into a robust model called EFDC+.

In addition to hydrodynamic and salinity and temperature transport simulation capabilities, EFDC+ is capable of simulating cohesive and non-cohesive sediment transport, near-field and far-field discharge dilution from multiple sources, the transport and fate of toxic contaminants in the water and sediment phases, the dissolved oxygen/nutrient process (i.e. eutrophication), Lagrangian particle tracking (LPT) and oil spill modeling. Special enhancements to the hydrodynamics of the code, including vegetation resistance, drying and wetting, hydraulic structure representation, wave current boundary layer interaction, and wave-induced currents, allow refined modeling of wetland and marsh systems, controlled-flow systems, and near-shore wave-induced currents and sediment transport. The EFDC code has been extensively tested and documented and used in 100's of modeling studies. The code is currently used by university, government, and engineering and environmental consulting organizations around the globe.

The DSI code is open source and we also work with our partners to provide ongoing updates and enhancements to EFDC+. An EFDC+ optimized graphical user interface called EFDC_Explorer has been developed by DSI to provide robust support for model construction, calibration and analysis. These two tools, EFDC+ and EFDC_Explorer make a power modeling system for environmental hydrodynamics.

The following overview of EFDC has been largely extracted from the EFDC Users Manual (Hamrick 1996). The model formulation was based on the principles expressed by the equations of motion, conservation of volume, and conservation of mass. Quantities computed by the model included three-dimensional velocities, surface elevation, vertical viscosity and diffusivity, temperature, salinity, and density.

The structure of the EFDC model includes four major modules: (1) a hydrodynamic model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics model (see Figure 1). The EFDC hydrodynamic model is composed of six transport modules including dynamics, dye, temperature, salinity, near field plume, and LPT (see Figure 2).

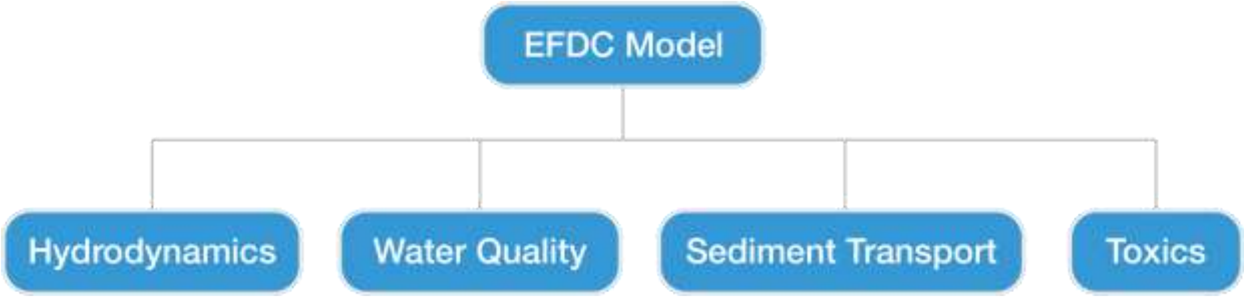

Figure 1 Primary modules of the EFDC model.

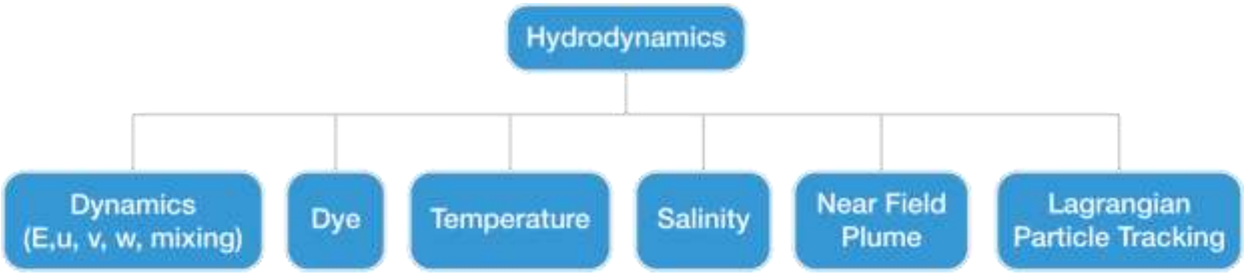

Figure 2 Structure of the EFDC hydrodynamic model.

2 Hydrodynamics and Salinity and Temperature Transport

The physics of the EFDC model and many aspects of the computational scheme are equivalent to the widely used Blumberg-Mellor model (Blumberg and Mellor 1987). The EFDC model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity, and temperature are also solved. The two turbulence parameter transport equations implement the Mellor-Yamada level 2.5 turbulence closure scheme (Mellor and Yamada 1982; Galperin et al. 1988). The EFDC model uses a stretched or sigma vertical coordinate and Cartesian, or curvilinear, orthogonal horizontal coordinates.

The numerical scheme employed in EFDC to solve the equations of motion uses second order accurate spatial finite differencing on a staggered or C grid. The model's time integration employs a second order accurate three-time level, finite difference scheme with an internal-external mode splitting procedure to separate the internal shear or baroclinic mode from the external free surface gravity wave or barotropic mode. The external mode solution is semi-implicit and simultaneously computes the two-dimensional (2D) surface elevation field by a preconditioned conjugate gradient procedure. The external solution is completed by the calculation of the depth average barotropic velocities using the new surface elevation field. The model's semi-implicit external solution allows large time steps that are constrained only by the stability criteria of the explicit central difference or high order upwind advection scheme (Smolarkiewicz and Margolin 1993) used for the nonlinear accelerations. Horizontal boundary conditions for the external mode solution include options for simultaneously specifying the surface elevation only, the characteristic of an incoming wave (Bennett and McIntosh 1982), free radiation of an outgoing wave (Bennett 1976; Blumberg and Kantha 1985), or the normal volumetric flux on arbitrary portions of the boundary. The EFDC model's internal momentum equation solution, at the same time step as the external solution, is implicit with respect to vertical diffusion. The internal solution of the momentum equations is in terms of the vertical profile of shear stress and velocity shear, which results in the simplest and most accurate form of the baroclinic pressure gradients and eliminates the over determined character of alternate internal mode formulations. Time splitting inherent in the three-time-level scheme is controlled by periodic insertion of a second order accurate two-time-level trapezoidal step. EFDC is also readily configured as a 2-D model in either the horizontal or vertical planes.

The EFDC model implements a second order accurate in space and time, mass conservation fractional step solution scheme for the Eulerian transport equations for salinity, temperature, suspended sediment, water quality constituents, and toxic contaminants. The transport equations are temporally integrated at the same time step or twice the time step of the momentum equation solution (Smolarkiewicz and Margolin 1993). The advective step of the transport solution uses either the central difference scheme used in the Blumberg-Mellor model or a hierarchy of positive definite upwind difference schemes. The highest accuracy upwind scheme, second order accurate in space and time, is based on a flux-corrected transport version Smolarkiewicz's multidimensional positive-definite advection transport algorithm (Smolarkiewicz and Clark, 1986; Smolarkiewicz and Grabowski 1990), which is monotonic and minimizes numerical diffusion. The horizontal diffusion step, if required, is explicit in time, whereas the vertical diffusion step is implicit. Horizontal boundary conditions include time variable material inflow concentrations, upwind outflow, and a damping relaxation specification of climatological boundary concentration. The NOAA Geophysical Fluid Dynamics Laboratory's atmospheric heat exchange model (Rosati and Miyakoda 1988) is implemented for the temperature transport equation.

3 Sediment Transport

There are two separate sediment transport sediment sub-models implemented in EFDC. The original EFDC code is capable of simulating the transport and fate of multiple size classes of cohesive and non-cohesive suspended sediment including bed deposition and resuspension. Water column transport is based on the same high order advection-diffusion scheme used for salinity and temperature. A number of options are included for the specification of settling velocities. Sediment mass conservative deposited bed formulations are included for both cohesive and noncohesive sediment. The deposited bed may be represented by a single layer or multiple layers. The multiple bed layer option provides a time since deposition versus vertical position in the bed relationship to be established. Water column/sediment bed interface elevation changes can be optionally incorporated into the hydrodynamic continuity equation. An optional one-dimensional (1-D) in the vertical, bed consolidation calculation can be performed for cohesive beds. Figure 3 shows a schematic of the sediment transport sub-model structure.

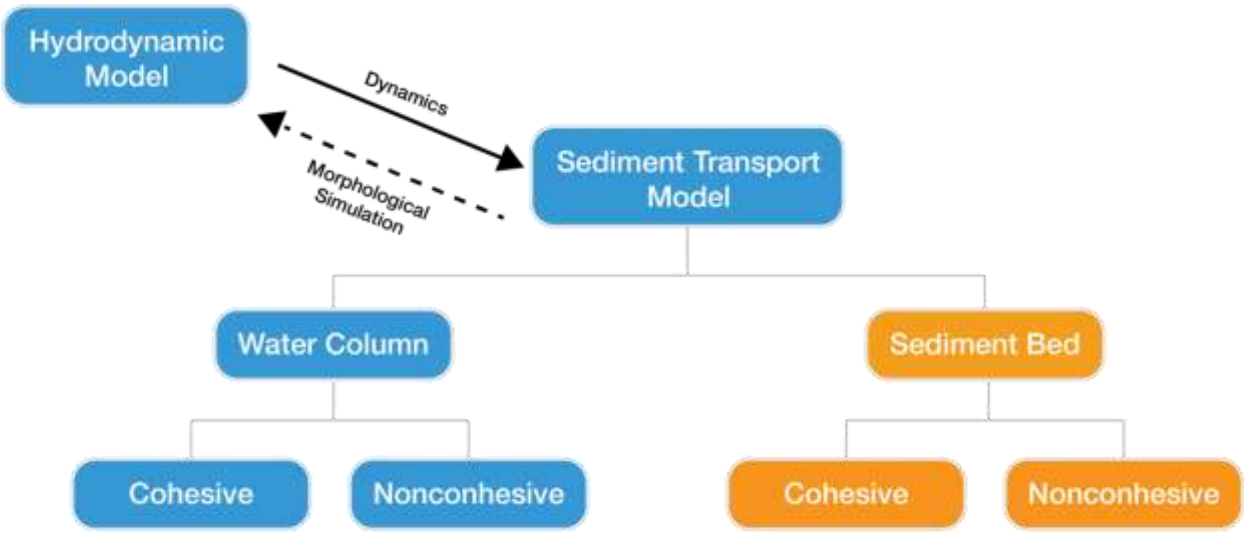

Figure 3 Structure of the EFDC sediment transport model.

A second sediment transport sub-model for EFDC is the SEDZLJ module which has been developed by Sandia National Laboratories and is implemented in EFDC+. A detailed description of the SEDZLJ implementation is available in *Sandia National Laboratories Environmental Fluid Dynamics Code: Sediment Transport User Manual* (Thanh, 2008). The new approach, shown in Figure 4, accounts for multiple sediment size classes, has a unified treatment of suspended load and bedload, and appropriately replicates bed armoring. The resulting flow, transport, and sediment dynamics model is an improvement to previous models because it may directly incorporate site-specific data, while maintaining a physically consistent, unified treatment of bedload and suspended load.

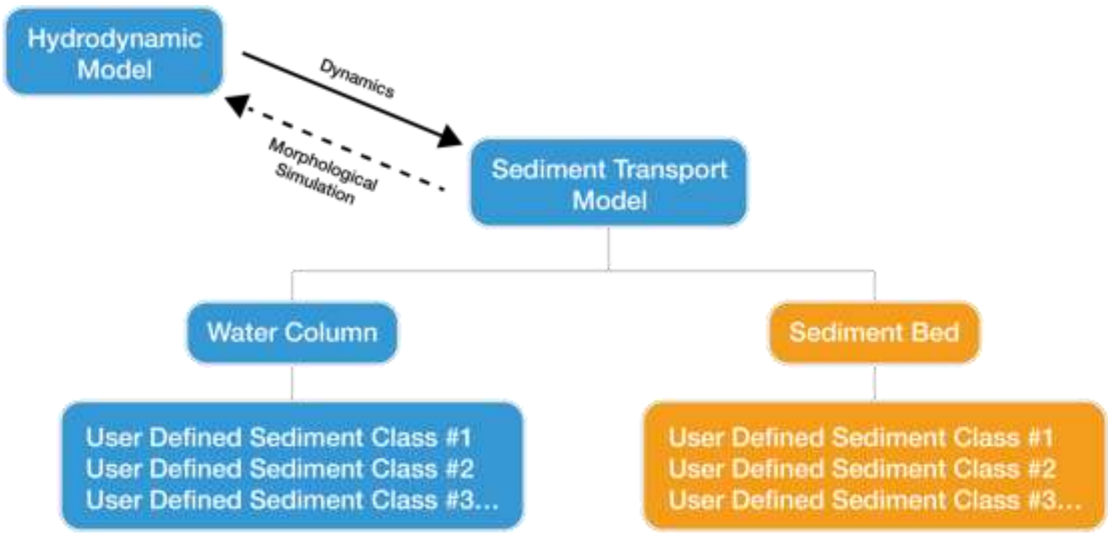

Figure 4 Structure of the SEDZLJ sediment transport model.

4 Toxic Contaminant Transport and Fate

The EFDC code includes two internal sub-models for simulating the transport and fate of toxic contaminants. A simple, single contaminant sub-model can be activated from the master input file. The simple model accounts for water and suspended sediment phase transport with equilibrium partitioning and a lumped first order reaction. Contaminant mass per unit area in the sediment bed is also simulated. The second, more complex, sub-model simulates the transport and fate of an arbitrary number of reacting contaminants in the water and sediment phases of both the water column and sediment bed. In this mode, the contaminant transport and fate simulation is functionally similar to the WASP5 TOXIC model (Ambrose et al. 1993), with the added flexibility of simulating an arbitrary number of contaminants, and the improved accuracy of utilizing more complex three-dimensional physical transport fields in a highly accurate numerical transport scheme. Water-sediment phases interaction may be represented by equilibrium or nonlinear sorption processes. In this mode, the multilayer sediment bed formulation is active, with sediment bed water volume and dissolved contaminant mass balances activated to allow contaminants to reenter the water column by sediment resuspension, pore water expulsion due to consolidation, and diffusion from the pore water into the water column. The complex contaminant model activates a subroutine describing reaction processes with appropriate reaction parameters provided by the toxic reaction processes input file. Figure 5 shows a schematic of the sediment transport/toxics sub-model structure.

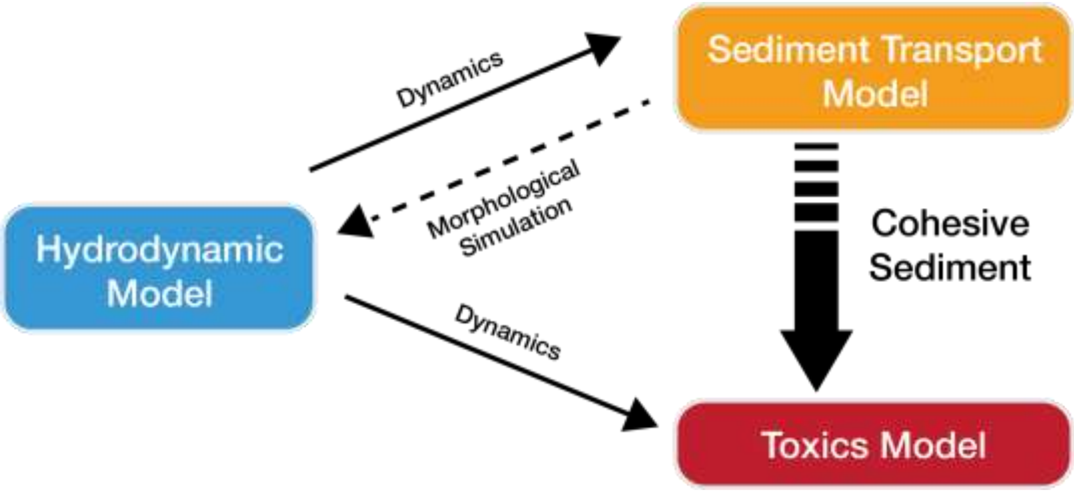

Figure 5 Structure of the EFDC toxics model.

5 Near-Field Discharge Dilution and Mixing Zone Analysis

In addition to the far-field transport and fate simulation capability incorporated into the EFDC code's water quality and toxic contaminant modules, the code includes a near-field discharge dilution and mixing zone module. The near field model is based on a Lagrangian buoyant jet and plume model (Frick 1984; Lee and Cheung 1990) and allows representation of submerged single and multiple port diffusers and buoyant surface jets. The near field model provides analysis capabilities similar to CORMIX (Jirka and Doneker 1991; Jirka and Akar 1991) while offering two distinct advantages. The first advantage is that a more realistic representation of ambient current and stratification conditions, provided directly by the EFDC hydrodynamic module, is incorporated into the analysis. The second advantage is that multiple discharges and multiple near field analysis times may be specified to account for varying ambient current and stratification conditions. For example, the analysis of 10 discharges under six ambient conditions each would require 60 executions of CORMIX, while the entire analysis of the 60 situations would be produced in a single EFDC simulation. The near-field simulation may be executed in two modes. The first provides virtual source information for representing the discharges in a standard EFDC far-field transport and fate simulation. In the second mode the near-field and far-field transport are directly coupled, using a virtual source formulation, to provide simultaneous near and far field transport and fate simulation.

6 Near-shore Wave-Induced Currents and Sediment Transport Extensions

The EFDC code includes a number of extensions for simulation of near-shore wave-induced current and non-cohesive sediment transport. The extensions include a wave-current boundary layer formulation similar to that of Grant and Madsen (1986); modifications of the hydrodynamic model's momentum equations to represent wave period-averaged Eulerian mean quantities; the inclusion of 3-D wave-induced radiation or Reynold's stresses in the momentum equations;

and modifications of the velocity fields in the transport equations to include advective transport by the wave-induced Stoke's drift. High-frequency surface wave fields are provided by an external wave refraction-diffraction model or by an internal mild slope equation submodel similar to that of Madsen and Larsen (1987). The internal refraction-diffraction computation is executed on a refined horizontal grid coincident with the main model's horizontal grid.

7 Wetland, Marsh, and Tidal Flat Simulation Extension

The EFDC model provides a number of enhancements for the simulation of flow and transport in wetlands, marshes, and tidal flats. The code allows for drying and wetting in shallow areas by a mass conservative scheme. The drying and wetting formulation is coupled to the mass transport equations in a manner that prevents negative concentrations of dissolved and suspended materials. A number of alternatives are in place in the model to simulate general discharge control structures such as weirs, spillways, culverts, and water surface elevation activated pumps. The effect of submerged and emergent plants is incorporated into the turbulence closure model and flow resistance formulation. Plant density and geometric characteristics of individual and composite plants are required as input for the vegetation resistance formulation. A simple soil moisture model, allowing rainfall infiltration and soil water loss due to evapotranspiration under dry conditions, is implemented. To represent narrow channels and canals in wetland, marsh and tidal flat systems, a sub-grid scale channel model is implemented. The sub-grid channel model allows a 1-D network in the horizontal channels to be dynamically coupled to the two-dimensional horizontal grid representing the wetland, marsh, or tidal flat system. Volume and mass exchanges between 2-D wetland cells and the 1-D channels are accounted for. The channels may continue to flow when the 2-D wetland cells become dry.

8 Water Quality and Eutrophication Simulation

The information of physical transport processes, both advective and diffusive, simulated by the hydrodynamic model can be used to account for the transport of passive substances including non-conservative water quality parameters. The EFDC code includes two internal eutrophication sub-models for water quality simulation (Park et al. 1995). The simple or reduced eutrophication model is functionally equivalent to the WASP5 EUTRO model (Ambrose et al. 1993).

A second, complex or full eutrophication, water quality model with 21 state variables has been developed and integrated with EFDC to form a three-dimensional Hydrodynamic-Eutrophication Model (HEM-3D). The model simulates spatial and temporal distributions of water quality parameters including dissolved oxygen, suspended algae (3 groups), various components of carbon, nitrogen, phosphorus and silica cycles, and fecal coliform bacteria. A sediment diagenesis process model with twenty-seven state variables has also been developed. The coupling of the sediment process model with the water quality model not only enhances the model's predictive capability of water quality parameters but also enables it to simulate the long-term changes in water quality conditions in response to changes in nutrient loadings.

This complex or full eutrophication model is functionally equivalent to the CE-QUAL-ICM or Chesapeake Bay Water Quality model (Cerco and Cole 1993). Both water column eutrophication models are coupled to a functionally equivalent implementation of the CE-QUAL-ICM sediment diagenesis or biogeochemical processes model (DiToro and Fitzpatrick 1993). The eutrophication models can be executed simultaneously with the hydrodynamic component of EFDC, or EFDC simulated hydrodynamic transport fields can be saved, allowing the EFDC code to be executed in a water quality only simulation mode. Figure 6 shows a schematic of the water quality sub-model structure.

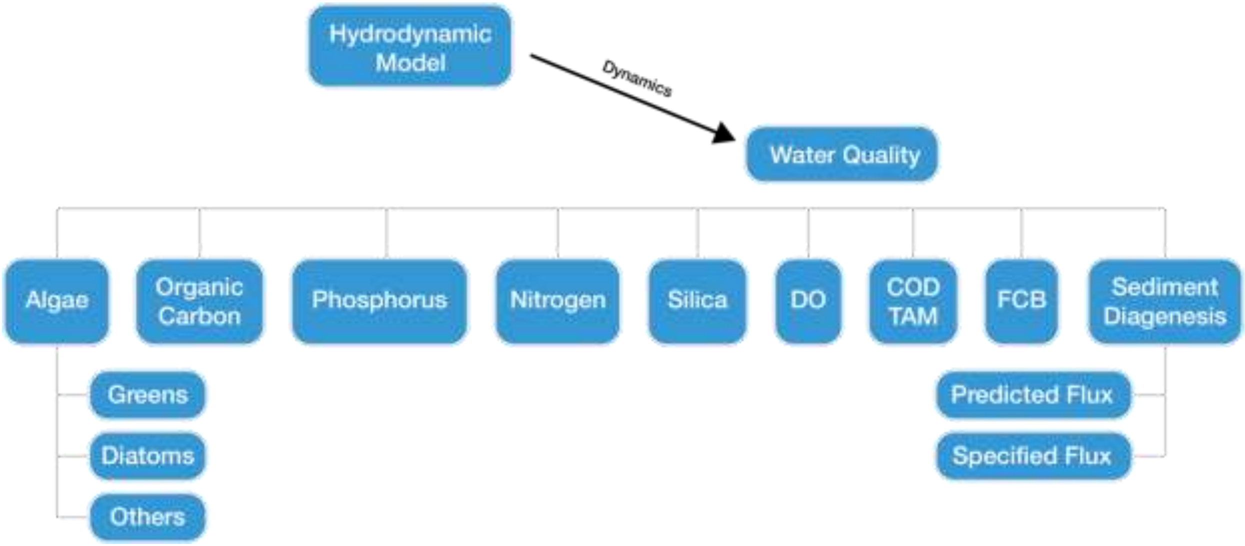

Figure 6 Structure of the EFDC water quality model.

The computational scheme used in the internal eutrophication models employs a fractional step extension of the same advective and diffusive algorithms used for salinity and temperature, which guarantee positive constituent concentrations. A novel ordering of the reaction sequence in the reactive source and sink fractional step allows the linearized reactions to be solved implicitly, further guaranteeing positive concentrations. The eutrophication models accept an arbitrary number of point and nonpoint source loadings as well as atmospheric and ground water loadings.

In addition to the internal eutrophication models, the EFDC model can be externally linked to the WASP5 model. In the external linking mode, the EFDC model generates WASP5 input files describing cell geometry and connectivity as well as advective and diffusive transport fields. For estuary simulation, the transport fields may be intratidally time averaged or intertidally time averaged using the averaging procedure described by Hamrick (1994).

9 Program Configuration

The EFDC code exists in only one generic version. A model application is specified entirely by information in the input files. To minimize memory requirements for specific applications, an executable file is created by adjusting the appropriate variable array size in the model's parameter file and compiling the source code. The EFDC model can be configured to execute all or a portion of a model application in reduced spatial dimension mode including 2-D depth or width averaged and 1-D cross section averaged. The number of layers used in the 3-D mode or 2-D width averaged mode is readily changed by one line of model input. Model grid sections specified as 2-D width averaged are allowed to have depth varying widths to provide representations equivalent to those of 2-D width averaged estuarine and reservoir models such as CE-QUAL-W2 (Cole and Buchak 1994).

10 Documentation

Extensive documentation of the EFDC model is available. Theoretical and computational aspects of the model are described by Hamrick (1992a). The model user's manual (Hamrick 1996) provides details on use of the EFDC input files. Input file templates are also included. A number of papers describe model applications and capabilities (Hamrick 1992b; Hamrick 1994; Hamrick and Wu 1996; Wu et al. 1996; and Xia et al. 2010).

A user's manual is available for the DSI developed pre/post processor EFDC_Explorer (Craig, 2016).

11 Computer Requirements

The original EFDC model was written in FORTRAN 77 but recent extensions to EFDC have been written in FORTRAN-90. The source code has been compiled and executed on most UNIX workstations (DEC Alpha, Hewlett-Packard, IBM RISC6000, Silicon Graphics, Sun and Sparc compatibles) Cray and Convex supercomputers, and PC compatible and Macintosh personal computers. Absoft, Lahey, and Intel compilers are supported on Windows® based sytems, while Absoft, Language Systems, and Motorola compilers are supported on Apple systems.

12 State Variables and Computed Output Variables of EFDC

Hydrodynamic models simulate velocity and transport fields, elevation of the free water surface; and bottom stress. The state variables of EFDC include: stage height or free water surface elevation; salinity, water temperature and velocity. A three-dimensional application of EFDC simulates velocity in three-dimensions (x,y,z) as the 'u' and 'v' horizontal (x,y) components and the 'w' vertical (z) component. Turbulent kinetic energy and turbulent macroscale length scale parameters are also included as state variables in EFDC. Water density is computed in EFDC as a function of water temperature and salinity. EFDC computes horizontal diffusivity as an output variable of the model from horizontal turbulent closure methods. EFDC also computes vertical eddy viscosity and vertical eddy diffusivity from vertical turbulence closure schemes as output variables of the model.

13 DSI Enhancements to EFDC

A number of key enhancements to the EFDC code, called the EFDC+ version, have been made by Dynamics Solution International as compared to the base EPA EFDC code (www.epa.gov/ceampubl/swater/efdc/index.htm). These enhancements have been made to EFDC to assist model development and application. The EFDC+ version enhancements include the following:

- Implementation of the Sigma Zed model (SGZ), (Craig, 2014). This version of EFDC significantly reduces the pressure gradient errors in stratified systems by allowing varied layer counts throughout the model domain. Each cell can use a different number of layers, though the number of layers for each cell is constant in time. The z coordinate system varies for each cell face, matching the number of active layers to the adjacent cells. The new version is computationally more efficient than a similarly configured Sigma Stretch grid, thus making models with 20 to 50 layers or more practical for typical projects.
- Implementation of a multi-threaded version of the EFDC model using Open Multi-threading Process technology (this version was formerly called EFDC_OMP). This allows the user to take full advantage of every CPU core to dramatically improve model run-times. DSI typically produces run times up to 4 times faster on a six core processor than the conventional single-threaded EFDC model.
- Dynamic memory allocation allows the user to use the same executable code for applications to different water bodies. Dynamic allocation eliminates the need to re-compile the EFDC code for different applications because of different maximum array sizes required to specify the computational grid domain and time series input data sets. Dynamic allocation also helps prevent inadvertent errors and provides better traceability for source code development.
- Enhanced heat exchange options that use equilibrium temperatures for the water and atmospheric interface and spatially variable sediment bed temperatures.
- Lagrangian Particle Tracking (LPT) sub-model has been added. Among useful applications are for oil spill modeling and emergency response simulations.
- A wind generated wave sub-model has been added to enable the computation of wind wave generated bed shear stress on sediment resuspension and wave induced currents.

- Incorporation of a Marine and Hydro-kinetic (MHK) friendly module for simulation of placement and potential effects of installing and operating turbines and wave energy converters in rivers, tidal channels, ocean currents, and other waterbodies. This code comes from Sandia National Laboratories modified Environmental Fluid Dynamics Code (SNL-EFDC) (James, 2010).
- Output snapshot controls for targeting specific periods for high frequency output within the standard regular output frequency.
- Streamlining the code for quicker execution times.
- Customizing linkage of model results for the Windows-based EFDC_Explorer graphical pre- and post-processor for EFDC.

14 EFDC_Explorer Description

EFDC_Explorer is a Windows-based pre- and post-processor for the EFDC model (Craig, 2016). It is designed to support model set-up, Cartesian and curvilinear grid generation, testing, calibration, and data visualization, including plots and animation, of model results (www.efdc-explorer.com).

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