

DRAFT



**US Army Corps
of Engineers®**
Engineer Research and
Development Center

Coastal Inlets Research Program

March 2002

Two-Dimensional Circulation Model M2D: Documentation and User's Guide

Adele Militello, Alan K. Zundel, and Frank Buonaiuto

ERDC/CHL TR-02-__

March 2002

Coastal Inlets Research Program

Two Dimensional Circulation Model M2D: Documentation and User's Guide

Adele Militello, Alan K. Zundel, and Frank Buonaiuto

Draft report

~~Approved for public release; distribution is unlimited~~

Prepared for

U.S. Army Corps of Engineers
Washington, DC 20314-1000

Contents

Draft report	2
1 Introduction to M2D	1
2 Governing Equations	3
3 Calculation Approach to Governing Equations	6
Rectilinear Grid	6
Linear Derivative and Coriolis Terms	7
Bottom Friction.....	8
Wind Stress.....	10
Wave Stress	10
Advective Terms.....	11
Nonlinear Continuity Terms	11
Cell Numbering	12
Courant Condition	14
4 Boundary Conditions	15
Tidal-Constituent Forcing Boundary Condition	15
Time-Series Water-Level Forcing Boundary Condition.....	16
Time-Series Flow-Rate Forcing Boundary Condition.....	17
Closed, Reflective Boundary Condition	19
Passive Open Boundary Condition	20
Cell Types.....	20
5 Flooding and Drying.....	22
Drying Algorithm	23
Flooding Algorithm	24
6 Surfacewater Modeling System Interface for M2D.....	25
7 Model Setup and File Structure	26
Grid Definition.....	26

Model Control.....	27
Initial Conditions and Forcing Data Files.....	31
Output Files	32
References.....	33

List of Figures

Figure 1.	Cell and variable definitions for M2D.....	7
Figure 2.	Bottom-friction coefficient adjustment versus total water depth.....	10
Figure 3.	Cell numbering system.....	13

List of Tables

Table 1.	Boundary condition types.....	15
Table 2.	Cell types and their function in M2D	21
Table 3.	Criteria for flooding and drying algorithms	23
Table 4.	Definitions of parameters in grid file.....	27
Table 5.	Model control file specifications	29

Preface

Development of the M2D model was supported by the Inlet Modeling System (IMS) Work Unit of the Coastal Inlets Research Program (CIRP) of Headquarters, U.S. Army Corps of Engineers. Ms. Mary A. Cialone was the IMS Principal Investigator and Dr. Nicholas C. Kraus was the CIRP Technical Leader. This report was prepared by Dr. Adele Militello, Coastal Analysis LLC, Dr. Alan K. Zundel, Environmental Modeling Research Laboratory, Brigham Young University, and Mr. Frank Buonaiuto, Marine Sciences Institute, State University of New York at Stony Brook. Dr. Militello was the Principal Investigator for the model development.

Work was performed under the general administrative supervision of Mr. Bruce Ebersole, Chief, HN-C, Mr. Thomas Richardson, Director, CHL.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.028317	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
miles (U.S. nautical)	1.852	kilometers
miles (U.S. statute)	1.609347	kilometers

1 Introduction to M2D

The U.S. Army Corps of Engineers (USACE), Coastal and Hydraulics Laboratory (CHL) has adopted the circulation model M2D for local applications, primarily in nearshore, inlet, and bay regions. M2D is computationally efficient, easy to set up, and has features required for many coastal engineering applications. In addition, it can be coupled to regional models, such as ADCIRC (Luettich, Westerink, and Scheffner 1992), through boundary conditions (Militello and Zundel 2002), providing flexibility for large-scale applications and connectivity.

The hydrodynamic model M2D is a two-dimensional, finite-difference numerical approximation of the depth-integrated continuity and momentum equations. The governing equations, finite-difference approximation, representation of bottom and surface stresses, flooding and drying algorithms, grid scheme, and boundary conditions are documented in this report.

Cells are defined on a staggered, rectilinear grid and can have constant or variable side lengths. The momentum equations are solved in a time-stepping manner first, followed by solution of the continuity equation, in which the updated velocities calculated by the momentum equations are applied. The solution scheme is explicit, although calculation of the advective and nonlinear-continuity terms specifies water-level and velocity values from two time steps, a necessary condition for numerical stability (Fischer 1959, Kowalick and Murty 1993). Features of the model include flooding and drying, wind-speed dependent (time-varying) wind-drag coefficient, variably-spaced bottom-friction coefficient, time- and space-varying wave-stress forcing, efficient grid storage in memory, and the convenience, through control statements, of independently turning on or off the advective terms, mixing terms, nonlinear continuity terms, and flooding and drying calculations. Additionally, model output is written in formats convenient for importing into commercially-available plotting packages.

A graphical interface for M2D has been implemented within the Surfacewater Modeling System (SMS) Versions 8.0 and above. Features of the M2D interface are grid development, control file specification, model runs, post-processing of results, and visualization. In addition, the SMS allows development of M2D grids from STWAVE (Smith, Resio, and Zundel 1999, Smith, Sherlock, and Resio 2001) grids, which is convenient for projects that require wave-stress forcing for M2D.

This report provides documentation for M2D and instruction on development of an M2D project within the SMS. Chapter 2 gives the governing equations solved in the model. Chapter 3 describes the finite-difference approximations and defines the cell numbering method. Chapter 4 describes the types of boundary conditions available in M2D. Chapter 5 provides the flooding and drying algorithms. Chapter 6 describes SMS interface for M2D and provides guidance for project development. Chapter 7 provides information on model set up and file structure. Appendix A gives example input and output files. Appendix B provides references for M2D development and applications. Appendices C through F describe results of model integrity tests. Appendix G provides results of tests for the flow-rate boundary condition.

2 Governing Equations

The two-dimensional, depth-integrated continuity and momentum equations solved by M2D are

$$\frac{\partial \eta}{\partial t} = -(h + \eta) \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) - u \frac{\partial (h + \eta)}{\partial x} - v \frac{\partial (h + \eta)}{\partial y} \quad (1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} = & -g \frac{\partial \eta}{\partial x} - u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} + 2a_h \frac{\partial^2 u}{\partial x^2} + fv - C_b \frac{u|U|}{(h + \eta)} \\ & + C_d \frac{\rho_a}{\rho_w} \frac{W^2 \cos(\theta)}{(h + \eta)} \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial t} = & -g \frac{\partial \eta}{\partial y} - u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} + 2a_h \frac{\partial^2 v}{\partial y^2} - fu - C_b \frac{v|U|}{(h + \eta)} \\ & + C_d \frac{\rho_a}{\rho_w} \frac{W^2 \sin(\theta)}{(h + \eta)} \end{aligned} \quad (3)$$

where h is the still-water depth, η is the deviation of the water-surface elevation from the still-water level, u is the depth-averaged current velocity parallel to the x -axis, v is the depth-averaged current velocity parallel to the y -axis, g is the gravitational acceleration, f is the Coriolis parameter, a_h is a horizontal coefficient of eddy viscosity, U is the total current velocity, C_b is an empirical bottom-stress coefficient, C_d is a wind drag coefficient, ρ_a is the density of air, ρ_w is the density of water, W is the wind speed, θ is the wind direction, and t is time. The convention for wind direction is specified to be 0 deg for wind from the east with angle increasing counterclockwise. The total current speed is

$$|U| = \sqrt{u^2 + v^2} \quad (4)$$

The Coriolis parameter is given by

$$f = 2\Omega \sin(\varphi) \quad (5)$$

where Ω is the angular frequency of the Earth's rotation, and ϕ is latitude.

The bottom friction coefficient is calculated by

$$C_b = \frac{g}{C^2} \quad (6)$$

where C is the Chezy coefficient given by

$$C = \frac{R^{1/6}}{n} \quad (7)$$

in which R is the hydraulic radius, and n is the Manning roughness coefficient.

The depth-mean horizontal eddy viscosity, a_h , is dependent on the total water depth, current speed, and bottom roughness, and it is given by (Falconer, 1980)

$$a_h = \frac{1}{2} \left(\frac{1}{56} g b + \eta \frac{|U|}{C^2} \right) \quad (8)$$

The form of the eddy viscosity coefficient given by Equation (8) results in mixing terms that are weakly nonlinear.

Accurate approximation of the wind-stress coefficient is of particular importance for wind-induced flow in very shallow water ($\approx < 5$ m). A short review of formulations relating to and describing the variable wind-stress coefficient is presented here.

The flux of momentum into the water column from the wind is specified as a function of the wind speed and wind-stress coefficient. The height of an anemometer above the water or land surface must be considered for accurate estimation of the wind-stress coefficient because wind speed varies logarithmically in the vertical direction for unstratified atmospheric conditions. A general law for the vertical wind profile is given by (Charnock, 1955; Hsu, 1988)

$$W_z = \frac{W_*}{\kappa} \ln \frac{Z}{Z_0} \quad (9)$$

where W_z is the wind speed at height Z above the surface, Z_0 is a surface roughness, W_* is the friction velocity, and κ is the von Kármán constant. The friction velocity is defined in terms of the surface wind stress as (Hsu, 1988)

$$\tau_0 = \rho_a W_*^2 = \rho_a K_m \frac{\partial W}{\partial z} \quad (10)$$

where K_m is an eddy viscosity coefficient. Under the assumption of nearly neutral atmospheric stability, the wind-stress coefficient over water at a height 10 m above the water surface, C_{10} , can be expressed as (Hsu, 1988)

$$C_{10} = \left(\frac{\kappa}{14.56 - 2 \ln W_{10}} \right)^2 \quad (11)$$

where W_{10} is the wind speed in m/s at 10 m above the surface. Development of Equation (11) includes the assumption of fully-developed seas. For measurements of wind speed made at heights other than 10 m, an approximation for the 10-m wind speed is (Shore Protection Manual, 1984)

$$W_{10} = W_z \left(\frac{10}{Z} \right)^{1/7} \quad (12)$$

Equations (11) and (12) have been successfully applied in modeling studies investigating motion in strongly wind-forced shallow embayments with typical depths ranging from 1 to 4 m (Brown et al. 1995, Kraus and Militello, 1999; Militello 1999). Calculated water level and current compared well with measurements, indicating that these formulations are satisfactory for estimation of the vertical wind profile and wind stress in very shallow-water systems.

3 Calculation Approach to Governing Equations

The rectilinear grid and discretization of the governing equations are described in this chapter. Information is also provided on cell numbering and the Courant stability criterion.

The solution method applied in solves the momentum equations first, then applies the updated velocities to the continuity equation solution (Fischer, 1959). The formulation of the finite-difference approximation presented here follows the computational order of the solution method applied in the model. Solution of the momentum equations is performed in two steps. In the first step, the momentum equations are solved without the advective terms, to obtain initial approximations of the updated velocities. The advective terms are then calculated and the contributions added to the initial approximations to obtain the completed updated velocities. Similarly, the continuity equation is solved without the nonlinear continuity terms to arrive at a first prediction of water level. The nonlinear continuity terms are then calculated and added to the solution for the water level.

Rectilinear Grid

Finite-difference approximations of the governing equations are applied to a discretized domain where cells are defined on a rectilinear grid (which can be regular or irregular) as shown in Figure 1. Each cell has indices i and j that correspond to its position along the x - and y -axes of the grid domain. Water-surface elevation is calculated at the cell center, whereas the x - and y -components of the current are calculated on the left face center and bottom face center of the cell, respectively. Because the best orientation of the grid may be such that the x - and y -axes do not correspond to geographical coordinates (N-S and E-W), cells in the grid are defined in a local (or grid) coordinate system. The local coordinate system is referenced to geographic coordinates by specification of the angle between the y -axis and true North.

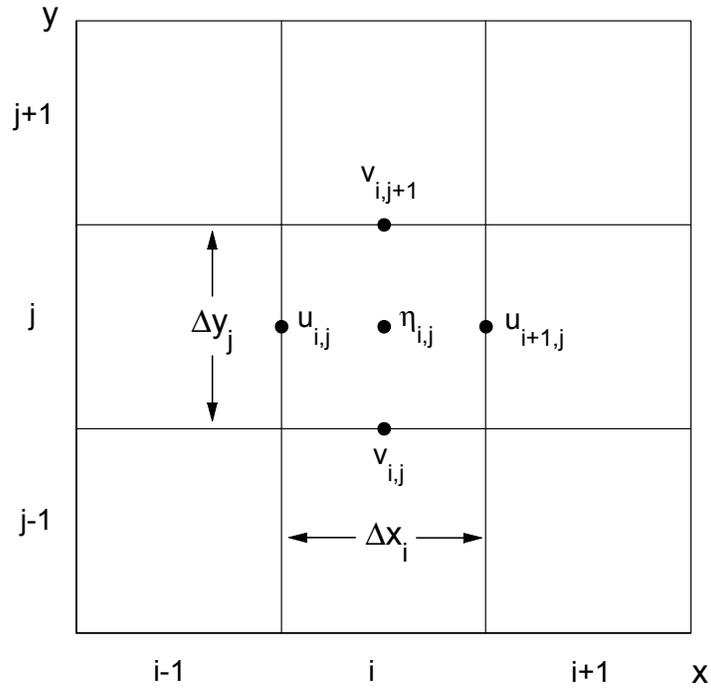


Figure1. Cell and variable definitions for M2D

Linear Derivative and Coriolis Terms

Spatial derivative terms in Equations (2) and (3), excluding advection, are approximated by

$$\frac{\partial \eta}{\partial x} \approx \frac{2\eta_{i,j}^k - \eta_{i-1,j}^k}{\Delta x_{i,j} + \Delta x_{i-1,j}} \quad (13)$$

$$\frac{\partial \eta}{\partial y} \approx \frac{2\eta_{i,j}^k - \eta_{i,j-1}^k}{\Delta y_{i,j} + \Delta y_{i,j-1}} \quad (14)$$

$$\frac{\partial^2 u}{\partial x^2} \approx \frac{\frac{u_{i+1,j}^k - u_{i,j}^k}{\Delta x_{i,j}} - \frac{u_{i,j}^k - u_{i-1,j}^k}{\Delta x_{i-1,j}}}{\Delta x_{i-1,j} + \Delta x_{i,j}} \quad (15)$$

$$\frac{\partial^2 v}{\partial y^2} \approx \frac{\frac{v_{i,j+1}^k - v_{i,j}^k}{\Delta y_{i,j}} - \frac{v_{i,j}^k - v_{i,j-1}^k}{\Delta y_{i,j-1}}}{\Delta y_{i,j-1} + \Delta y_{i,j}} \quad (16)$$

where the subscripts i and j specify the cell location on the grid, $\Delta x_{i,j}$ and $\Delta y_{i,j}$ are the cell-side lengths parallel to the x - and y -axes, respectively (see Figure 1), and the superscript k indicates the previous time step. Values of Δx and Δy are constant parallel to the y and x -axes, respectively, but can vary along the x and y -axes, respectively. For example, $\Delta x_{i,j} = \Delta x_{i,j+1}$ but $\Delta x_{i,j}$ may or may not equal $\Delta x_{i-1,j}$.

The coefficient of eddy viscosity is calculated as

$$b_g = \frac{1}{2} \left(\frac{1}{56} g h_{i,j} + \eta_{i,j}^k \frac{|U_{i,j}^k|}{C_{i,j}^{k,2}} \right) \quad (17)$$

for Manning's $n > 0$. For frictionless cells, specified by $n = 0$, $a_h = 0.02 \text{ m}^2/\text{s}$ (if the user has selected to include the mixing terms in the computations). The total current speed is given by

$$|U_{i,j}^k| = \sqrt{u_{i,j}^k{}^2 + v_{i,j}^k{}^2} \quad (18)$$

The Coriolis terms are given by

$$fv = f_{i,j} v_{i,j}^k \quad (19)$$

$$fu = f_{i,j} u_{i,j}^k \quad (20)$$

Bottom Friction

Bottom friction terms are calculated by

$$\frac{C_b u |U|}{h + \eta g} = \frac{C_{b,u} u_{i,j}^k |U_{i,j}^k|}{h_{i,j} + \eta_{i,j}^k} \quad (21)$$

$$\frac{C_b v |U|}{h + \eta g} = \frac{C_{b,v} v_{i,j}^k |U_{i,j}^k|}{h_{i,j} + \eta_{i,j}^k} \quad (22)$$

The bottom-friction coefficient, C_b , depends on the hydraulic radius, R , which, in turn, depends on the cell dimension, Δs , in the corresponding flow direction. The hydraulic radius for a given cell is calculated by

$$R_{i,j}^k = \frac{d_{i,j} + \eta_{i,j}^k |\Delta s_{i,j}|}{P_{i,j}^k} \quad (23)$$

where $P_{i,j}$ is the wetted perimeter of the cell, and Δs denotes Δx or Δy for application of Equation (23) to the x - or y -momentum equation, respectively. The wetted perimeter is taken to be equal to Δs if a cell has no impermeable walls. If walls are present, the wetted perimeter is calculated by

$$P_{i,j}^k = \Delta s_{i,j} + m d_{i,j} + \eta_{i,j}^k i \quad (24)$$

where m is the number of wall boundaries on sides parallel to the component of flow corresponding to s . For example, in the case of flow along a one-cell-wide channel aligned with the x -axis, the wetted perimeter would be calculated as $P = \Delta x + 2b + \eta c$ at all cells in the channel. If the channel is two cells wide, then the wetted perimeter for the x -momentum equation would be calculated as $P = \Delta x + b + \eta c$. The formulation of the bottom-friction coefficient takes into account wall friction, but does not distinguish it from friction along the channel bottom. In addition, calculation of the wetted perimeter does not account for changes in depth between adjacent cells (increase in wetted surface area).

If water in a cell approaches a thin layer, numerical instability may arise and unrealistically large values of water level and current speed can be calculated. This numerical problem is more apparent than real because water creeping onto a dry surface is expected to experience large frictional resistance. Stability in very shallow water is enhanced within M2D by adjustment of the bottom-friction coefficient by the following formulation

$$C_{b,adjusted} = C_b \left[\frac{H}{H_0} \right]^{-\alpha} \exp^{-\alpha \frac{d_{i,j} + \eta_{i,j}^k |j|}{H_0}} \quad (25)$$

where the subscript *adjusted* denotes the modified bottom-friction coefficient, and α is a parameter that controls the gradient of the increase of the bottom-friction coefficient as the water depth approaches zero. The bottom-friction coefficient can vary within the range C_b to $2C_b$ with the adjustment scaled by the exponential expression given within Equation (25). Figure 2 shows the depth-dependent adjustment of the bottom-friction coefficient as given by the exponential formulation with the parameter α set to 10. Significant increases in the bottom-friction coefficient occur for small water depth, particularly less than 0.1 m because of the presence of large roughness elements relative to the water depth. Thus, modification of the bottom-friction coefficient from its normal value is restricted to small water depth. For depths greater than approximately 0.2 m, modification of the bottom-friction coefficient is small.

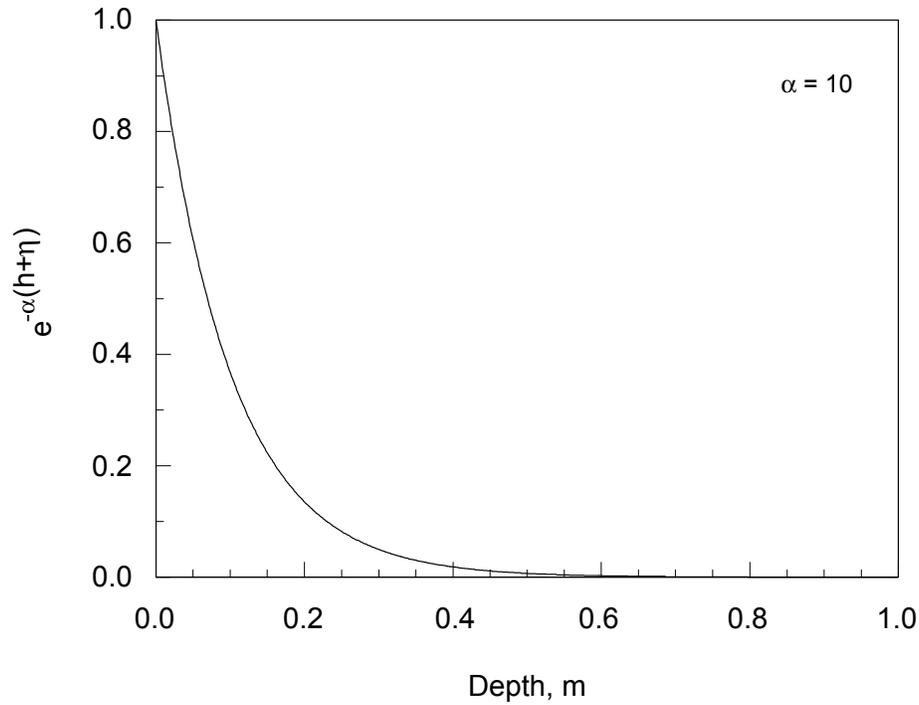


Figure 2. Bottom-friction coefficient adjustment versus total water depth.

Wind Stress

Wind-stress terms are calculated by

$$C_d \frac{\rho_a}{\rho_w} \frac{W^2 \cos \theta}{b + \eta} = C_d \frac{\rho_a}{\rho_w} \frac{W^{k+1} \cos \theta^{k+1}}{d_{i,j} + \eta_{i,j}^k} \quad (26)$$

$$C_d \frac{\rho_a}{\rho_w} \frac{W^2 \sin \theta}{b + \eta} = C_d \frac{\rho_a}{\rho_w} \frac{W^{k+1} \sin \theta^{k+1}}{d_{i,j} + \eta_{i,j}^k} \quad (27)$$

where C_d is calculated by Equation (11) where W_{10} has been calculated from W . Height of the anemometer is specified in an input file. Wind forcing in M2D can vary over time, but is spatially homogenous over space.

Wave Stress

To be added.

Advective Terms

To be added.

Nonlinear Continuity Terms

The nonlinear continuity equation is treated in two steps. The first step solves for that part of the continuity equation that includes h , and the second step solves for terms including η . The first step is performed over the entire calculation domain before the second step is performed. The finite-difference approximations to terms in Equation (1) involving h are

$$h \frac{\partial h}{\partial t} + \frac{\partial v}{\partial y} h_{i,j} \left(\frac{v_{i+1,j}^{k+1} - u_{i,j}^{k+1}}{\Delta x_{i,j}} + \frac{v_{i,j+1}^{k+1} - v_{i,j}^{k+1}}{\Delta y_{i,j}} \right) \quad (28)$$

$$u \frac{\partial h}{\partial x} \approx \frac{v_{i+1,j}^{k+1} + u_{i,j}^{k+1}}{2} \left(\frac{v_{i+1,j} - h_{i-1,j}}{\Delta x_{i+1,j} + \Delta x_{i-1,j}} + \Delta x_{i,j} \right) \quad (29)$$

$$v \frac{\partial h}{\partial y} \approx \frac{v_{i,j+1}^{k+1} + v_{i,j}^{k+1}}{2} \left(\frac{v_{i,j+1} - h_{i,j-1}}{\Delta y_{i,j+1} + \Delta y_{i,j-1}} + \Delta y_{i,j} \right) \quad (30)$$

The nonlinear continuity terms are approximated by

$$\eta \frac{\partial \eta}{\partial t} + \frac{\partial v}{\partial y} \left(\frac{1}{2} \eta_{i,j}^{k+1} + \eta_{i,j}^k \right) \left(\frac{v_{i+1,j}^{k+1} - u_{i,j}^{k+1}}{\Delta x_{i,j}} + \frac{v_{i,j+1}^{k+1} - v_{i,j}^{k+1}}{\Delta y_{i,j}} \right) \quad (31)$$

$$u \frac{\partial \eta}{\partial x} = \frac{u_{i+1,j}^{k+1} + u_{i,j}^{k+1}}{2} \left[\frac{1}{2} \left(\frac{\eta_{i+1,j}^{k+1} - \eta_{i-1,j}^{k+1}}{0.5(\Delta x_{i-1,j} + \Delta x_{i+1,j}) + \Delta x_{i,j}} \right) + \frac{1}{2} \left(\frac{\eta_{i+1,j}^k - \eta_{i-1,j}^k}{0.5(\Delta x_{i-1,j} + \Delta x_{i+1,j}) + \Delta x_{i,j}} \right) \right] \quad (32)$$

$$v \frac{\partial \eta}{\partial y} = \frac{v_{i,j+1}^{k+1} + v_{i,j}^{k+1}}{2} \left[\frac{1}{2} \left(\frac{\eta_{i,j+1}^{k+1} - \eta_{i,j-1}^{k+1}}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j+1}) + \Delta y_{i,j}} \right) + \frac{1}{2} \left(\frac{\eta_{i,j+1}^k - \eta_{i,j-1}^k}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j+1}) + \Delta y_{i,j}} \right) \right] \quad (33)$$

To conserve mass, the order of calculation of Equations (31), (32), and (33) must be reversed from the other terms in the equations of motion. Following the procedure of Roberts and Weiss (1966), Flather and Heaps (1975) reversed the order of computations for the advective terms at every time step. The order reversal in their numerical solution centers the computations in time and space in their scheme.

Cell Numbering

M2D stores its numerical grid in an array rather than a matrix, which saves memory for large or irregular grid domains. The numbering scheme for the computational grid is designed to be efficient such that regions that never become computationally active do not have to be stored. For model domains that have complex shorelines, this feature can save substantial computer memory. On the other hand, for simple grids, more memory may be required because pointing arrays are necessary for cell indexing.

The cell-numbering system does not require row and column indexing, but instead assigns each cell a unique identification number. Flather and Heaps (1975) applied a similar cell-numbering system so that only cells included in hydrodynamic calculations were stored. Non-computational regions of the grid, such as the mainland and islands, do not require assigned cell numbers, so they do not occupy space in memory. Figure 3 illustrates the cell-numbering system that includes a non-computational region indicated by hatching. Cell identification numbers of neighbors adjacent to a particular cell are stored in a pointing matrix within the model. For example, Cell 9 has neighbors with cell identification numbers 12, 10, 4, and 8 moving from top, to right, bottom, and left, respectively. This clockwise order of referencing neighbor cells will be taken as convention. Locations where no cells exist, such as beyond the computational domain or in non-computational regions, such as islands within the domain, are designated with a cell number of 0. For example, Cell 11 in Figure 3 lies on the boundary of the grid domain and also resides next to a non-computational area. The neighbor-cell specifications for Cell 11 would be stored as 14, 0, 6, and 0. The grid does not contain any cells with cell number of zero; this value is used in neighbor specification to indicate that a computational cell does not exist at a particular location. If a cell is removed from computations, it retains its original cell number, but its neighbors do not "see" it, and calculations are performed for an impermeable wall at the interfaces of the neighbors and the inactive cell.

In implementation of the finite-difference computations, the i,j indexing is replaced by cell identification numbers. For example, the water-surface gradients given by Equations (13) and (14) for the i,j coordinates corresponding to Cell 17 would be calculated as

$$\frac{\partial \eta}{\partial x} \approx \frac{2\eta_{17}^k - \eta_{16}^k}{\Delta x_{17} + \Delta x_{16}} \quad (34)$$

$$\frac{\partial \eta}{\partial y} \approx \frac{2(\eta_{17}^k - \eta_{12}^k)}{(\Delta y_{17} + \Delta y_{12})} \quad (35)$$

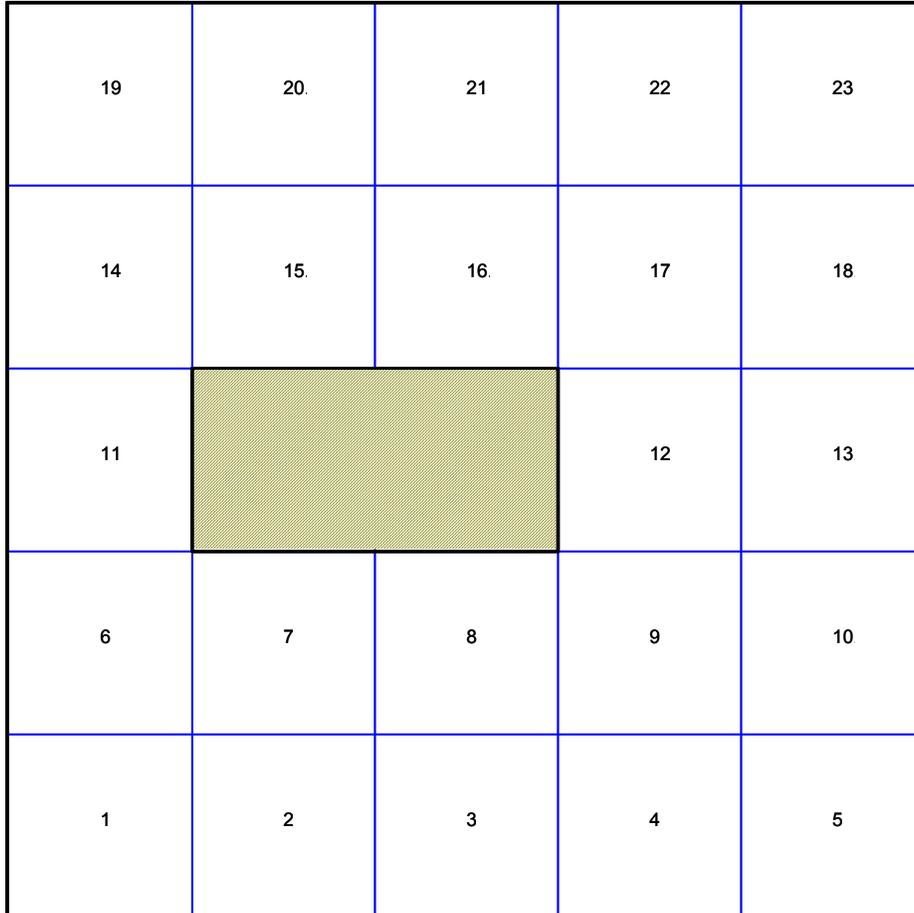


Figure 3. Cell numbering system.

Removal of a cell from computations can be achieved by setting its type to inactive and changing its value to zero at locations where it is referenced as a neighbor. The inactive cell would remain in the grid and retain its original cell number. As an example, if Cell 3 were to be changed to an inactive type cell, the neighbor specifications for Cell 4 would be changed from 9, 5, 0, 3 to 9, 5, 0, 0. Specifications for Cell 3 would remain the same, except that the type would be changed to inactive (Type 0).

Courant Condition

An initial estimate of the maximum time step for a grid is calculated from the Courant number ξ , given by

$$\xi \equiv u \frac{\Delta t}{\Delta s} \quad (36)$$

(Richtmyer and Morton, 1957). The theoretical maximum value of the Courant number is unity for stability of a linear, finite-difference hydrodynamic model. Practical application of M2D requires that the Courant number be less than 1, with a maximum of approximately 0.7, where u is taken to be \sqrt{gh} . For a variably-spaced grid, the maximum time step must be set by application of the Courant stability condition to the cell that requires the smallest time step. For given cell dimensions, a deep channel would require specification of a shorter time step than a shallower region.

4 Boundary Conditions

Five types of boundary conditions are implemented in M2D, and these can be distinguished as specifying forcing and non-forcing boundaries. Table 1 lists the boundary-condition types and contains a short description of each. Details of each boundary-condition type are presented below, including finite-difference approximations specific to each type. The finite-difference approximations presented for the boundary conditions are specified for flow parallel to the x axis. Analogous approximations have been implemented for flow parallel to the y axis, but are not presented because they are redundant.

Boundary Condition	Description
Tidal-constituent water-level forcing	Water level specified as a sum of tidal constituents
Time-series water-level forcing	Water level specified from a time-series input file
Time-series flow-rate forcing	Flow rate specified from a time-series input file
Closed, reflective (non-forcing)	Impermeable boundary, velocity must flow parallel to the boundary
Passive open (non-forcing)	Open boundary specified by assigning flow rate through boundary cell identical to adjacent interior cell

If cell (i,j) is forced directly by a boundary condition, then the variable through which that boundary condition enters depends on the location of the boundary relative to cell (i,j) . Boundary conditions must enter the continuity equation from one or both of cells $(i+1,j)$ and $(i,j+1)$, depending on the grid and boundary configuration. Boundary conditions must enter the momentum equation through one or both of cells $(i-1,j)$, and $(i,j-1)$.

Tidal-Constituent Forcing Boundary Condition

Water-level forcing can be applied by either tidal constituents or by specification of time-series water level. The tidal-constituent forcing in M2D can accommodate as many as eight components of the astronomical tide. The user can select from the following constituents: M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , M_4 , and M_6 . Although the M_4 and M_6 constituents are harmonics, they can be generated in

continental shelf areas and may be present as components of the tidal forcing at the grid boundary. Specification of tidal constituents requires input information for the local amplitude and phase values. The applied tidal forcing is simple and does not include advanced tidal calculations or relations to Greenwich tidal parameters (Schureman, 1924).

The water-level forcing boundary condition enters the momentum equations as a component of the surface-slope calculation. For the x -momentum equation, the tidal boundary is applied as

$$\frac{\partial \eta}{\partial x} = \frac{\eta_{i,j}^k - \eta_b^k}{\Delta x_{i,j}} \quad (37)$$

where η_b denotes the tidally-specified water level.

Application of the tidal boundary condition to the continuity equation allows direct computation of the water level at a cell just inside the boundary. For cell i, j positioned to the left of the tidal boundary, the water level is calculated by

$$\eta_{i,j}^{k+1} = \eta_b - \frac{\eta_b - \eta_{i-1,j}^k}{0.5 \Delta x_{i-1,j} + \Delta x_{i,j}} \Delta x_{i,j} \quad (38)$$

where a cell size of $\Delta x_{i,j}$ has been assumed for the position of the tidal boundary.

Time-Series Water-Level Forcing Boundary Condition

The time-series water-level forcing boundary condition is specified by water levels read into the model from an input file. Time increments of the forcing data are not required to be equal to, or in multiple increments of, the model time step. Because the model will usually have smaller time steps than the water-level forcing data input, M2D must be instructed on treatment of the water-level boundary value between times that its value is specified in the input file. One option is to keep the water-level constant between input water-level values. A second option is to linearly interpolate in time between input water-level values. The boundary condition input file for water level contains a parameter that sets the option.

Implementation of the time-series water-level forcing boundary condition in M2D is slightly different from that of the tidal-boundary condition in that the time-series forcing cell resides on the computational grid. As with the tidal forcing, the time-series water-level forcing enters into the momentum equation through the water-surface gradient. The boundary is applied as

$$\frac{\partial \eta}{\partial x} = 2 \frac{\eta_{i,j}^k - \eta_b^k}{\Delta x_{i,j} - \Delta x_{i-1,j}} \quad (39)$$

where $\eta_b^k = \eta_{i-1,j}^k$. Once the value of the time-series water-level at the boundary is specified and placed into the water-elevation array, the water-surface gradient for a cell adjacent to the boundary can be calculated in the same manner as an internal cell that does not reside on a boundary.

Time-Series Flow-Rate Forcing Boundary Condition

The time-series flow-rate forcing boundary condition can be applied at locations where the flow rate is known. Typical examples where this boundary condition is applied are natural tributaries (rivers, streams, and creeks), controlled-discharge canals, and anthropogenic intake or discharge locations such as for power plant cooling water or treatment plant outfalls.

A flow-rate boundary condition specifies discharge at one or more cells on the grid boundary. For each cell, the equation for flow rate Q is applied. This equation is

$$Q = AU \quad (40)$$

where A is the cross-sectional area and here U is the current velocity normal to the cross-sectional area. Applying Eq. (40) to the x and y directions gives

$$Q_x = [(h + \eta)\Delta y]u \quad (41)$$

$$Q_y = [(h + \eta)\Delta x]v \quad (42)$$

where Q_x and Q_y are flow rates parallel to the x and y axes, respectively.

The flow-rate boundary condition in M2D can only be specified for flow along one axis at any given boundary cell. The grid file provides the cell and boundary information to M2D so that it applies the appropriate equation. The flow direction along an axis is specified as positive if $Q > 0$ and is negative if $Q < 0$. For example, if a flow-rate boundary is specified such that the discharge is parallel to the x axis and $Q_x > 0$, then the flow is directed toward the positive x direction.

Implementation of the flow-rate boundary condition varies depending on whether it enters through the continuity equation or one of the momentum equations. If the flow-rate boundary condition is applied through a cell face corresponding to $(i,j+1)$ or $(i+1,j)$, then it enters through the continuity equation. If the flow-rate boundary condition is applied through at cell face corresponding

to $(i-1,j)$ or $(i,j-1)$, then it will enter through the x or y momentum equation, respectively.

For a flow-rate boundary condition that enters through the continuity equation, the boundary water-surface elevation is set equal to that of the adjacent interior cell as

$$\eta_b^{k+1} = \eta_{adj}^k \quad (43)$$

where the subscript b denotes the forcing boundary cell, and η_{adj} denotes the water-surface elevation at the adjacent interior cell (a cell that is adjacent to a boundary cell and is not a forcing cell). For flow rate specified parallel to the x axis, the velocity for the boundary cell u_b^{k+1} is calculated based on the flow direction as

$$u_b^{k+1} = \frac{Q^{k+1}}{h_b \Delta y}, \quad Q^{k+1} \geq 0 \quad (44)$$

$$u_b^{k+1} = \frac{Q^{k+1}}{(h_b + \eta_b^{k+1}) \Delta y}, \quad Q^{k+1} < 0 \quad (45)$$

where Q^{k+1} is the flow rate specified at the boundary at time $k+1$. For flow rate specified parallel to the y axis, the velocity for the boundary cell v_b^{k+1} is calculated based on the flow direction as

$$v_b^{k+1} = \frac{Q^{k+1}}{h_b \Delta x}, \quad Q^{k+1} \geq 0 \quad (46)$$

$$v_b^{k+1} = \frac{Q^{k+1}}{(h_b + \eta_b^{k+1}) \Delta x}, \quad Q^{k+1} < 0 \quad (47)$$

Specification of boundary variables for flow-rate forcing boundary information that enters through one of the momentum equations is also dependent on the flow direction. For the x momentum equation, the water-surface elevation is prescribed as

$$\eta_b^{k+1} = \eta_{adj}^k, \quad Q^{k+1} \geq 0 \quad (48)$$

$$\eta_b^{k+1} = \eta_b^k - h_b \frac{(u_{adj}^k - u_b^k)}{\Delta x} \Delta t, \quad Q^{k+1} < 0 \quad (49)$$

and the velocity is

$$u_b^{k+1} = \frac{Q^{k+1}}{(h_b + \eta_b^{k+1}) \Delta y} \quad (50)$$

For the flow-rate boundary condition entering through the y momentum equation, Eqn. (48) applies and Eqn. (49) becomes

$$\eta_b^{k+1} = \eta_b^k - h_b \frac{(v_{adj}^k - u_b^k)}{\Delta y} \Delta t, \quad Q^{k+1} < 0 \quad (51)$$

The velocity at the boundary is given by

$$v_b^{k+1} = \frac{Q^{k+1}}{(h_b + \eta_b^{k+1}) \Delta x} \quad (52)$$

In addition to the variable specification on the boundaries, the velocities of the interior cells adjacent to the flow-rate forcing boundaries are specified as

$$u_{adj}^{k+1} = \frac{Q_b^{k+1}}{(h_{adj} + \eta_b^{k+1}) \Delta y} \quad (53)$$

for boundary flow prescribed parallel to the x axis, and

$$v_{adj}^{k+1} = \frac{Q_b^{k+1}}{(h_{adj} + \eta_b^{k+1}) \Delta x} \quad (54)$$

for boundary flow prescribed parallel to the y axis. Equations (53) and (54) are applied only when the flow rate boundary condition enters through a momentum equation.

If a cell is specified as a flow-rate forcing cell, M2D redefines the cell attributes so that no cross flow (normal to the direction of the specified flow rate) can occur. Walls are defined on the cell faces through which normally-directed flow could normally occur.

Closed, Reflective Boundary Condition

The closed, reflective boundary condition is applied at impermeable boundaries. These boundaries behave as walls; water can flow parallel to the wall face, but not through it. Specification of the velocity at the closed boundary for either the momentum or continuity equation is

$$u_b^{k+1} = 0 \quad (55)$$

The spatial gradient of velocity for the continuity equation is calculated by

$$\frac{\partial u}{\partial x} = \frac{Q_b^{k+1} - u_{i,j}^{k+1}}{\Delta x_{i,j}} = -\frac{u_{i,j}^{k+1}}{\Delta x_{i,j}} \quad (56)$$

Passive Open Boundary Condition

The passive open boundary condition can be applied at open regions of the grid where information on water elevation or flow rate is not available. Typically, this type of open boundary condition would be applied along lateral nearshore boundaries where wave forcing is significant or at channels that extend beyond the grid domain and are not a source of significant forcing for the system.

Boundary condition description to be added.

Cell Types

Five cell types can be specified within M2D. The cell-type specifications instruct the model in treatment of each cell. Table 2 gives the cell types and their function. The inactive cell type can be applied to specify cells where the equations of motion are not applied (no calculations performed for inactive cells), such as at islands. The computational grid can be developed in an efficient manner that does not require inclusion of inactive cells. Thus, this cell type should be avoided to minimize memory requirements, but it can be included in the grid.

The active regular cell type is specified for the majority of cells in a typical computational domain. Active regular cells are not forcing cells. The water-level and flow-rate forcing boundary cell types specify the water elevation and flow rate, respectively, at boundary cells.

The dry cell type corresponds to a cell that has dried during the simulation. The dry cell is not included in hydrodynamic calculations until it is rewetted. Upon rewetting, the cell type is changed to the active regular type.

Table 2. Cell types and their function in M2D

Type Index	Type	Function
0	Inactive	Cell not included as part of calculation domain
1	Active regular cell	Non-forcing, regular cell
2	Water-level forcing boundary cell	Water-level specified as a boundary condition at this cell
3	Flow-rate forcing boundary cell	Flow rate specified as a boundary condition at this cell
4	Dry cell	Cell dry and not included in hydrodynamic calculations until rewetted. Upon rewetting, cell type changed to Type 1

5 Flooding and Drying

Numerical modeling of shallow-water lagoons with expansive tidal or wind-tidal flats is most accurately performed if realistic and robust flooding and drying algorithms are included in the computations. Representation of flooding and drying also eliminates the need to modify grid depth to avoid artificially-induced instabilities or to specify unrealistic walls around the domain. Numerical simulation of flooding and drying of cells or elements in hydrodynamic models has been performed with various techniques such as application of barrier and weir equations (Reid and Bodine, 1968; Butler, 1978; Wanstrath, 1978) and moving boundaries (Yeh and Chou, 1979). The approach taken in M2D removes and returns cells to the active computational domain so that the land-water interface position is defined by location of adjacent active and dry cells. The algorithms minimize changes in water-level gradient.

Successful implementation of a flooding and drying algorithm requires that shocks, flutter, and reflections be minimized or nonexistent; patterns of drying be realistic; and the flooding and drying of cells occur under physically realistic conditions. Flutter occurs when one or more cells rapidly alternate between being flooded and dried (for example, several times between successive time steps). During cell flooding and drying, gradients in water level or current can be induced that set up artificial oscillations. These oscillations can be interpreted by a model as the correct condition for flooding or drying of a cell. Thus, measures should be taken to reduce the artificial oscillations upon inception of flooding or drying and to control the response of the model to these oscillations.

Criteria were established for the flooding and drying algorithms implemented in M2D and are given in Table 3. The criteria were specified so that the algorithms would behave realistically, and numerical problems, such as oscillations and flutter, would be minimized. Two of the criteria involve specification of a number of time steps for a cell to be wet or dry. These requirements force the cell to remain open or closed so that terms in the equations of motion can approach equilibrium in the vicinity of the newly wetted or dried cell. In numerical tests described in Appendix F, the required number of time steps for a cell to remain wet or dry was set to 30 for the 1D tests and 100 for the 2D test. These specifications in the numerical tests reduced flutter, although flutter was not completely eliminated. The number of time steps specified for cells to remain wet or dry may depend on cell size and time step and can be varied for different applications.

Table 3. Criteria for flooding and drying algorithms	
Flooding	Comments
1. Water level must exceed a certain elevation in adjacent cells	Transfer of physically meaningful water volume, avoid transfer of unphysical amount, avoid flutter
2. Water must be moving toward dry cell and be of elevation greater than elevation of dry cell	Takes into account wind-induced setup
3. Once a cell is wet, it must remain wet until adjacent cells have been wet for at least M_d time steps	Reduces flutter
Drying	Comments
1. η less than still-water depth, h	Definition of drying
2. Once a cell is dry, it must remain dry for N_d time steps	Reduces flutter

Drying Algorithm

The algorithm for drying cells has four basic steps: (1) Test the water depth to determine if the cell has dried; (2) If the cell has dried, remove the volume of water that was in the cell at the previous time step and distribute it over the active computational domain; (3) Modify the cell boundary type for the dried cell; and (4) Recalculate water elevations and currents for the previous time step. The drying algorithm was developed to be realistic in that a dry cell does not contain permanently residual or "virtual" water. In addition, Step (2) ensures that mass is conserved.

Every wet cell is checked to determine whether or not it has dried after new water-level and velocity values have been calculated over the model domain. The criterion for a cell to be dry is

$$H_{i,j} = h_{i,j} + \eta_{i,j} \leq H_{cr} \quad (57)$$

where $H_{i,j}$ is the total water depth, and H_{cr} is a depth below which drying is assumed to occur. For the numerical tests presented in Appendix B, H_{cr} was set to 0.1 m.

During numerical computation of drying, the effective time when a cell becomes dry is at step $k+1$. However, because the calculated depth is usually negative, the time when the depth was zero would have occurred between time steps. To reduce shocks associated with the refilling of cells after the depth has become negative, the drying algorithm in M2D moves back in time to the previous step and forces the cell to dry then.

Once the newly dried cell is removed from computations and the water level is adjusted, the cell boundary types are re-specified and the newly dried cell is designated as a Type 4 (dry) cell. Cell boundaries at interfaces of the newly dried cell and its four neighbors are set to closed, reflecting boundaries. In the

final step of the drying algorithm, the momentum and continuity equations are resolved for the previous time step.

Flooding Algorithm

The flooding algorithm implements a technique developed to minimize shocks during the cell-wetting process. Shocks occur if the balance of terms in the equations of motion is artificially disrupted, and reflections are induced at the wetted cell wall. Propagation of the shock produces two undesirable phenomena: instabilities and flutter. Development of the flooding algorithm presented here was subject to the requirements that shocks be minimized and wetting occur under physically realistic conditions.

The algorithm for flooding cells is comprised of four basic steps:
(1) Determine if a cell is to be flooded; (2) Calculate the volume of water to be transferred to the flooding cell; (3) Transfer water to the cell to be flooded; and (4) Modify the cell-boundary type for the newly wetted cell.

At each time step, dry cells are evaluated to determine if conditions are appropriate for flooding. For a cell to be flooded, it must first remain dry for a specified number of time steps. This requirement helps to reduce flutter from repeated consecutive opening and closing of a cell. If a cell has met the time requirement for remaining dry, the water levels and direction of the currents at surrounding cells are checked. A cell can only be flooded if the water level in at least one adjacent cell is higher than in the dry cell, and the corresponding current is flowing toward the dry cell. The requirement for water to be flowing toward the dry cell is necessary to prevent flooding under strong wind forcing, during which water may be driven away from the dry cell while the water level in the adjacent (downwind) cell is higher than in the dry cell.

Once the water level and current conditions are favorable for flooding, a water level for the dry cell is calculated based on the water-surface elevations of surrounding cells where water levels meet the criteria stated above. Potentially, four water-surface elevation values are available for calculating water level in the dry cell. Calculation of water level for the cell to be flooded is calculated as the average of water-surface elevation values in all surrounding cells that meet the criteria stated above.

After the water levels are updated, the boundaries at the interfaces of the flooded cell and adjacent cells are opened so that water can flow freely through them. The cell type of the flooded cell is set to Type 1 (active regular cell; see Table 2).

6 Surfacewater Modeling System Interface for M2D

A graphical interface for M2D has been implemented within the SMS Versions 8.0 and higher. The interface has capabilities for grid development, parameter specification, control file setup, model runs, post-processing of global field values, and visualization. This chapter provides instruction on creating and working with M2D projects within the SMS.

To be added.

7 Model Setup and File Structure

Setup of M2D requires development of a computational grid and preparation of one or more input files. This section describes the structure of files required to run the M2D model and its output files. All input and output files to M2D are ASCII. Unless otherwise noted, files are free format.

Grid Definition

The grid file for M2D is structured such that all information pertaining to a cell is found on the same line as the cell identification number. This format is convenient for the user so that once a cell is located in the grid file, its properties are easily viewed or modified. The grid file contains information that is not used within M2D, but is retained for user reference and post processing.

The first line of the grid file is a header line that describes the columns of information that make up the grid. Only one line is allowed for the header. All lines after the first specify cell information. Cells are defined by their cell identification number and the cell numbers of adjacent cells, referred to by local direction (North, East, South, West). These directions are relative to the local (grid) coordinate system defined by the grid, which may or may not be aligned with global geographic coordinates. For example, if the grid is oriented with its y axis parallel to North-South, then the grid coordinate system is aligned with global geographic coordinates. If the grid is rotated at an angle such that its y axis is not parallel to North-South, then the local coordinate system is not aligned with global geographic coordinates. In the latter case, directions specified in the grid file and within M2D correspond to the local coordinate system.

Each line describing a cell consists of the following information:

Cell number, NC, EC, SC, WC, NB, EB, SB, WB, IACTV, DX, DY, H, N,
ROW, COL, LAT, X-DIST, Y-DIST

where descriptions of parameters are given in Table 4.

Cell-center coordinates (*x*-dist and *y*-dist) can be given in any Cartesian coordinate system, such as State Plane or UTM. M2D does not apply the cell-center coordinates in calculations, but does export the values in global files of water-surface elevation and velocity. Because no specific coordinate system is required, the user can apply a coordinate system that is convenient for the particular application.

Table 4. Definitions of parameters in grid file	
Parameter	Description¹
Cell Number	Cell identification number (referred to as ICELL within M2D)
NC	Cell number of cell adjacent to and north of ICELL
EC	Cell number of cell adjacent to and east of ICELL
SC	Cell number of cell adjacent to and south of ICELL
WC	Cell number of cell adjacent to and west of ICELL
NB	Boundary type at northern edge of ICELL
EB	Boundary type at eastern edge of ICELL
SB	Boundary type at southern edge of ICELL
WB	Boundary type at western edge of ICELL
IACTV	Cell type or active status
DX	Cell width parallel to the <i>x</i> axis (m)
DY	Cell width parallel to the <i>y</i> axis (m)
H	Still-water depth relative to a user-specified datum (m)
N	Manning roughness coefficient (m/s ^{1/3})
ROW	Row position of cell ²
COL	Column position of cell ²
LAT	Latitude (decimal degrees)
X-DIST	<i>X</i> coordinate or distance from grid origin ² (m) ^{3,4}
Y-DIST	<i>Y</i> coordinate or distance from grid origin ² (m) ^{3,4}
1. Directional description (North, East, South, West) refers to the grid coordinate system. 2. Parameter is not used in M2D calculations 3. Parameter is not used in M2D calculations, but is written in global output files 4. Coordinates are located at cell centers	

Model Control

Model control specifications are defined in an input file called “m2d.m2c.” Each line of m2d.m2c contains the parameter or character string followed by a description. The description is optional as M2D does not read it. File names for i/o are user-specified for M2D and are listed as input parameters in m2d.m2c. Names of files are limited to 50 characters in length. There must be at least one

space between the parameter or character string and the description. Information contained in the m2d.m2c file is listed in Table 5 in the required order. The format of the m2d.m2c file is the same for all model and project configurations. All parameters listed in Table 5 must be included in the m2d.m2c file.

Three types of output files can be specified: time-series of variables or terms at specified cells, time-series of variables along a profile (not discussed), or global values of variables at specified times. To specify time-series of variable or terms, cell numbers are identified as locations to output information and a separate file is created to save each variable or term. Files denoted in Table 5 as “Cell-specification files” list cell identification numbers at which time-series information is stored. Each line of a cell-specification file contains one cell identification number.

Files denoted in Table 5 as “Time-specification files” are for global velocity and elevation output, and contain a list of times to save data. Times are specified in number of elapsed hours since the beginning of the simulation. Each line in the file contains one value of time and times must be in sequential order. The interval between successive output can vary through the simulation. For example, a time specification file may have output times prescribed as 0, 1, 2, 2.5, 3, 3.5, 4, 4.25, and 5 hr.

Table 5. Model control file specifications	
Parameter	Description
Anemometer height (m)	Height of anemometer above water or land surface
Ratio of density of air to density of water	Set to 0.0012 for typical applications
Angle between True North and y-axis of grid (deg)	Defined by grid orientation
Grid origin x-coordinate	Location of x position of Cell 1
Grid origin y-coordinate	Location of y position of Cell 1
Time step (s)	Model time step
Linear or nonlinear continuity equation	Flag for inclusion of finite-amplitude terms in the continuity equation. Flag settings: 0 = do not include, 1 = include
Include advective terms	Flag for inclusion of advective terms in the momentum equation. Flag settings: 0 = do not include, 1 = include
Include mixing terms	Flag for inclusion of mixing terms in the momentum equation. Flag settings: 0 = do not include, 1 = include
Allow wetting and drying	Flag for allowing flooding and drying. Flag settings: 0 = do not allow, 1 = allow.
Depth (m) to begin drying cells	If wetting and drying are allowed, drying will occur if the total depth in a cell is less than or equal to the depth specified here.
Calculate sediment transport**	Flag for calculation of sediment transport. Flag settings: 0 = do not calculate, 1 = calculate
Sediment transport time step**	Time step for sediment transport calculations
Starting Julian Day (YYDDD OR DDD)	Date of beginning of simulation
Start time (hr)	Time of beginning of simulation
Realization time (hr)	Duration of simulation
Ramp duration (day)	Duration of ramp
Steering Module elapsed time	Cumulative time at beginning of present simulation; applied for multiple simulations with Steering Module
Time to write output for hot start (hr)	Time when hot start output is to be written. Use a value of 0 if no hot start information is to be saved,
Grid file name	Name of grid file (required)
Initial conditions file name	Name of file containing initial conditions. If starting the simulation from quiescent conditions, use "default" (without the quotes) instead of a file name.
Tidal constituents file name	Name of file containing tidal constituents.
Wind input file name	Name of file containing wind speed and direction (required).
Include radiation stresses	Flag for inclusion of radiation stress forcing. Flag settings: 0 = no radiation stress forcing, 1 = include radiation stress forcing

STWAVE simulation file	Name of STWAVE *.sim file
Radiation stress file	Name of radiation stress file *.rad.
Hot start output file name	Name of hot start output file .
Time-specification file for vector plot output	Name of file containing times for vector plot (global u, v) output .
Time-specification file for global elevation output	Name of file containing times for global elevation output .
Time-series output cell-specification file	Name of file containing cell numbers for time-series output of u , v , η , and nonlinear terms .
Flow rate output time-series cell-specification file	Name of file containing cell numbers for flow rate output .
Time between output file writes (s) for u , v , η time-series file	Time should be a multiple of the simulation time step
Time between output file writes (s) for profile file	Time should be a multiple of the simulation time step
Time between output file writes (s) for flow-rate file	Time should be a multiple of the simulation time step
Time-series output file for u	Name of file to contain u time series .
Time-series output file for v	Name of file to contain v time series .
Time-series output file for η	Name of file to contain η time series .
Time-series output file for $u\partial\eta/\partial x$	Name of file to contain $u\partial\eta/\partial x$ time series .
Time-series output file for $v\partial\eta/\partial y$	Name of file to contain $v\partial\eta/\partial y$ time series .
Time-series output file for $\eta\partial u/\partial x$	Name of file to contain $\eta\partial u/\partial x$ time series .
Time-series output file for $\eta\partial v/\partial y$	Name of file to contain $\eta\partial v/\partial y$ time series .
Time-series output file for $u\partial u/\partial x$	Name of file to contain $u\partial u/\partial x$ time series .
Time-series output file for $u\partial v/\partial x$	Name of file to contain $u\partial v/\partial x$ time series .
Time-series output file for $v\partial u/\partial y$	Name of file to contain $v\partial u/\partial y$ time series .
Time-series output file for $v\partial v/\partial y$	Name of file to contain $v\partial v/\partial y$ time series .
Time-series output file for x-component of bottom friction	Name of file to contain time series of x-component of bottom friction .
Time-series output file for y-component of bottom friction	Name of file to contain time series of y-component of bottom friction .
Time-series output file for x-component of wind stress	Name of file to contain time series of x-component of wind stress .
Time-series output file for y-component of wind stress	Name of file to contain time series of y-component of wind stress .
Flow rate output file for Q_x	Name of file to contain time series of Q_x .
Flow rate output file for Q_y	Name of file to contain time series of Q_y .
Prefix for vector output file name	M2D appends “.m2v” to the user-specified prefix when naming the vector output file.
Prefix for global elevation output file name	M2D appends “.m2s” to the user-specified prefix

	when naming the global elevation file.
Prefix for global bottom change output file name	M2D appends “.m2s” to the user-specified prefix when naming the global bottom change file.
HDRIVER file name	Name of file containing water-surface elevation forcing information.
QDRIVER file name	Name of file containing flow-rate forcing information.
* Use “none” or “NONE” if no hot start output for this variable is specified.	
**Sediment transport in M2D is under development and is not presently available for the end user.	

Initial Conditions and Forcing Data Files

An initial conditions file provide the water-surface elevation and velocity at the beginning of the simulation at all cells. Each line in the initial conditions file contains four values: cell number, η , u , and v . Water level is given in m and velocity components are given in m/s.

Forcing data for M2D can be from water-level time series, discharge time series, tidal constituents, and wind. Input requirements for each of these is described. Specification of forcing by water-surface elevation and discharge are nearly identical and are presented together.

M2D recognizes whether time series of water level and/or discharge are applied as forcing by identification of forcing cells in the grid file. If time-series water level (discharge) driving cells are found, M2D opens the HDRIVER (QDRIVER) (see Table 5). The first line of the HDRIVER (QDRIVER) file contains two integer values. The first value specifies the number of files containing water-surface elevation forcing time series. The second number is the total number of cells forced by water-surface elevation values.

The second line contains the name of a data file that contains the forcing data. The third line of the HDRIVER (QDRIVER) file contains the number of cells that are driven by the data contained in the file listed in the second line, and an interpolation parameter. The interpolation parameter specifies whether or not the forcing data are interpolated between model time steps. For example, water-level forcing data may be available every hour, but the model time step might be 30 s. If the interpolation parameter is set to 1, values of water level at the forcing boundaries are interpolated at each model time step. If the interpolation parameter is set to 0, no interpolation takes place. Interpolation of discharge is treated in the same manner. Following the first and second lines of the HDRIVER (QDRIVER) file is a list of cell numbers that are forced by the time-series data given in the forcing data file.

If more than one forcing data file is applied for water level or discharge, information is specified exactly as described above for all sets of forcing data and placed in the HDRIVER or QDRIVER file below the information for the first file.

Files containing time-series water level or discharge forcing data are specified to have two values on each line. The first value is the time stamp. The time is specified in hours since the beginning of the simulation. So, at $t = 0$, the time stamp would be 0.0 and at $t = 1$ day, the time stamp would be 24.0. The second value is water-surface elevation (m) relative to the same datum as the grid for water-level forcing data, or flow rate (m^3/s) for discharge data. Time stamps must start at 0.0 and end at or after the ending time of the simulation.

Wind speed and direction are given in the user-specified wind file listed in `m2d.m2c`. The wind forcing file contains three values on each line. The first value is the time stamp in hr since the beginning of the simulation. The second value is the wind speed in m/s and the third value is direction in deg. The convention for the input wind direction is 0 deg indicates wind blowing from the north, and 90 deg indicates wind blowing from the east. Wind speed must be positive. Conversion to the wind-direction convention given for Equations (2) and (3) is conducted internally within M2D.

The tidal-constituent forcing file contains nine lines. The first line is a header that can identify the source of the tidal-constituent information. The header line is ignored by M2D. Each of the remaining lines contain the local amplitude (m) and phase (deg) of the water level for a specific tidal constituent. The constituents specified on lines 2 through 9 are (in order of appearance): M_2 , N_2 , S_2 , K_2 , K_1 , O_1 , M_4 , and M_6 .

Output Files

The two types of output files described are time series of a variable or term and global variable files. Time-series output files contain a header line followed by the calculated time-series values. The header specifies the cell numbers above columns of output. Cell numbers in the header are written as “C#” where # denotes the cell number. The “C” is placed in the header to distinguish the cell number from data in plotting packages (software will read the information in as a character string). Lines following the header contain a time stamp (fractional days) and values of the variable or term.

Global files can be created for water-surface elevation, velocity, and depth change. File formats consist of sets of global variable values output at times specified by the user. Each set of information in the file contains a line with the time stamp, followed by lines containing the x,y position of each cell followed by the value of the variable, such as η . For velocity, these lines contain u and v . The global information is saved for each cell in the grid and written in ascending order of cell identification number. File extensions of `.m2s` are applied to scalar fields and `.m2v` to vector fields.

Units for time series and global files are standard metric. Water-surface elevation is given in m and velocity is given in m/s.

References

- Brown, C. A., Kraus, N. C., and Militello A., 1995: Hydrodynamic Modeling for Assessing Engineering Alternatives for Elevating the Kennedy Causeway, Corpus Christi, Texas. *Proceedings of the 4th International Estuarine and Coastal Modeling Conference*, American Society of Civil Engineers, ASCE Press, New York, 681-694.
- Brown, C. A., and Militello, A., 1997: *Packery Channel Feasibility Study: Circulation and Water Level; Report 2 of a Two-Part Series*. TAMU-CC-CBI-96-07, Conrad Blucher Institute for Surveying and Science, Texas A&M University-Corpus Christi, Corpus Christi, Texas.
- Butler, H. L., 1978: Coastal Flood Simulation in Stretched Coordinates. *Proceedings of the Sixteenth Coastal Engineering Conference*, American Society of Civil Engineers, 1,030-1,048.
- Charnock, H., 1955: Wind Stress on a Water Surface. *Quarterly Journal of the Royal Meteorological Society*, 81, 639-640.
- Falconer, R. A., 1980: Modelling of Planform Influence on Circulation in Harbors. *Proceedings of the Seventeenth Coastal Engineering Conference*, American Society of Civil Engineers, 2,726-2,744.
- Fischer, G., 1959: Ein numerisches Verfahren zur Errechnung von Windstau und Gezeiten in Randmeeren. *Tellus*, 2, 1, 60-76.
- Flather, R. A., and Heaps, N. S., 1975: Tidal Computations for Morecambe Bay. *Geophysical Journal of the Royal Astronomical Society London*, A210, 423-436.
- Hsu, S. A., 1988: *Coastal Meteorology*. Academic Press, San Diego.
- Kowalik, Z., and Murty, T. S., 1993: *Numerical Modeling of Ocean Dynamics*. World Scientific, New Jersey, 481 pp.
- Kraus, N. C., and Militello, A. 1999: Hydraulic Study of Multiple Inlet System: East Matagorda Bay, Texas. *Journal of Hydraulic Engineering*, 125, 3, 224-232.
- Luettich, R. A., Westerink, J. J., and Scheffner, N. W. 1992. ADCIRC: An Advanced Three-dimensional Circulation Model for Shelves, Coasts, and Estuaries; Report 1, Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL. Technical Report DRP-92-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Militello, A. 2000. Hydrodynamic Modeling of a Sea-Breeze Dominated Shallow Embayment, Baffin Bay, Texas. *Sixth International Estuarine and Coastal Modeling Conference*, American Society of Civil Engineers, ASCE Press, New York, 795-810.

- Militello, A., and Zundel, A. K. 2002. Automated Coupling of Regional and Local Circulation Models through Boundary Condition Specification. *Proceedings of the Fifth International Conference on Hydroinformatics*, International Association of Hydraulic Research (in press).
- Nguyen, K. D., and Martin, J.-M., 1988: A Two-dimensional Fourth-order Simulation for Scalar Transport in Estuaries and Coastal Seas. *Estuarine, Coastal and Shelf Science*, 27, 263-281.
- Reid, R. O., and Bodine, B. R., 1968: Numerical Model for Storm Surges in Galveston Bay. *Journal of the Waterways and Harbors Division*, American Society of Civil Engineers, 94, WW1, 33-57.
- Richtmyer, R. D., and Morton, K. W., 1967: *Difference Methods for Initial-Value Problems*. Interscience Publishers, New York, 405 pp.
- Roache, P. J., 1976: *Computational Fluid Dynamics*. Hermosa Publishers, Albuquerque, New Mexico, 446 pp.
- Roberts, K. V., and Weiss, N. O., 1966: Convective Difference Schemes. *Mathematics of Computation*, 20, 94, 272-299.
- Schureman, P., 1924: A Manual of the Harmonic Analysis and Prediction of Tides. U.S. Coast and Geodetic Survey, Special Publication 98, 426 pp.
- Shore Protection Manual, 1984: Fourth ed., 2 Vols., U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, U.S. Government Printing Office, Washington, D. C.
- Smith, J. M., Resio, D. T., and Zundel, A. K. (1999). "STWAVE: steady-state spectral wave model, Report 1: User's manual for STWAVE version 2.0," Instructional Report CHL-99-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Smith, J. M., Sherlock, A. R., and Resio, D. T., (2001). "STWAVE: steady-state spectral wave model: User's manual for STWAVE version 3.0," Supplemental Report ERDC/CHL SR-01-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Wanstrath, J. J., 1978: An Open-Coast Mathematical Storm Surge Model with Coastal Flooding for Louisiana, Report 1, Theory and Application. Miscellaneous Paper H-78-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.
- Yeh, G.-T., and Chou, F.-K., 1978: Moving Boundary Numerical Surge Model. *Journal of the Waterway Port Coastal and Ocean Division*, American Society of Civil Engineers, 105, WW3, 247-263.