Elemental Wetting and Drying in the ADCIRC Hydrodynamic Model: Upgrades and Documentation for ADCIRC Version 34.XX

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INTRODUCTION

Versions 26.XX and lower of the 2D/3D hydrodynamic model ADCIRC (Luettich et al, 1992, Westerink et al, 1994) made no allowance for the flooding or drying of tidal flats during a tidal cycle or for the inundation and recession of water from low lying coastal lands in response to coastal storms. Rather, ADCIRC assumed the land-water boundary was fixed regardless of the water surface elevation. To accommodate this assumption, (i) bathymetric water depths had to be artificially deepened near shore so that nodes never became dry during falling water levels and (ii) coastlines were assumed to represent infinitely high vertical walls which water piled up against during rising water levels. While these assumptions are reasonable for modeling large scale coastal flows, they improperly represent frictional dissipation and finite amplitude nonlinearities in near shore regions and they also prohibit the overland propagation of flood waters associated with storm surge. As a result, coastal storm surge elevations are often over-estimated and the extent of inundation, a critical parameter in the use of hydrodynamic models for coastal planning, can not accurately be assessed.

Version 27.XX expanded the capabilities of ADCIRC by adding an elemental wetting and drying algorithm (Luettich and Westerink, 1995b) based on a literature review and idealized test applications (Luettich and Westerink, 1995a,b). Since this initial implementation in ADCIRC, a variety of field applications have demonstrated the utility of the wetting and drying capability while also identifying several improvements that could be made. This experience together with the incompatibility of the initial wetting and drying algorithm with both ADCIRC-3D and a parallel version of ADCIRC-2D (presently under development), suggested the need for a significant re-write of this algorithm. The methodology and implementation of this new algorithm are described below.

MODIFICATIONS MADE IN ADCIRC VERSION 27.XX TO FACILITATE WETTING AND DRYING

ADCIRC uses a time splitting algorithm to efficiently solve for hydrodynamic variables of interest, (Luettich et al., 1992). Each time step, the vertically-integrated continuity equation (in Generalized Wave Continuity Equation form) is solved to obtain the spatial distribution of water surface elevation. After the surface elevation computation has been completed, either the vertically-integrated momentum equations (for a 2D vertically-integrated solution) or the full 3D momentum equations (for a 3D solution) are solved for the velocity field.

As described in Luettich and Westerink (1995b), several modifications were made to the original ADCIRC formulation to facilitate the initial implementation of wetting and drying and enhance overall model performance. These are summarized below since they are not contained in the primary ADCIRC reference documentation (Luettich et al., 1992, Westerink et al., 1994).

First, ADCIRC was modified to allow the option of using either a fully consistent or a lumped formulation of the linear time derivative terms in the GWCE. (The desired formulation is selected using the model setup code ADCSETUP.) Mathematically, this means that the Galerkin weighted residual statement for the GWCE was changed from

$$\left\langle \frac{\partial^2 \zeta}{\partial t^2}, \phi_i \right\rangle_\Omega + \left\langle \tau_o \frac{\partial \zeta}{\partial t}, \phi_i \right\rangle_\Omega + \left\langle gh \frac{\partial \zeta}{\partial x}, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega + \left\langle gh \frac{\partial \zeta}{\partial y}, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega$$

$$= -E_{h2} \left\langle \frac{\partial^2 \zeta}{\partial x \partial t}, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega - E_{h2} \left\langle \frac{\partial^2 \zeta}{\partial y \partial t}, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega + \left\langle U \frac{\partial \zeta}{\partial t}, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega + \left\langle V \frac{\partial \zeta}{\partial t}, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega \qquad (1)$$

$$+ \left\langle W_x, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega + \left\langle W_y, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega - \int_{\Gamma_Q} \left(\frac{\partial Q_{n*}}{\partial t} + \tau_o Q_{n*} \right) \phi_i \, d\Gamma \qquad i = 1, \ldots N$$

to

$$\left(\frac{\partial^2 \zeta}{\partial t^2} + \tau_o \frac{\partial \zeta}{\partial t} \right)_i \left\langle \phi_i \right\rangle_\Omega + \left\langle gh \frac{\partial \zeta}{\partial x}, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega + \left\langle gh \frac{\partial \zeta}{\partial y}, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega$$

$$= -E_{h2} \left\langle \frac{\partial^2 \zeta}{\partial x \partial t}, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega - E_{h2} \left\langle \frac{\partial^2 \zeta}{\partial y \partial t}, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega + \left\langle U \frac{\partial \zeta}{\partial t}, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega + \left\langle V \frac{\partial \zeta}{\partial t}, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega \qquad (2)$$

$$+ \left\langle W_x, \frac{\partial \phi_i}{\partial x} \right\rangle_\Omega + \left\langle W_y, \frac{\partial \phi_i}{\partial y} \right\rangle_\Omega - \int_{\Gamma_Q} \left(\frac{\partial Q_{n*}}{\partial t} + \tau_o Q_{n*} \right) \phi_i \, d\Gamma \qquad i = 1, \ldots N$$

where all variables are as defined in Luettich et al., (1992).

For any node i, the consistent formulation distributes the contribution of the first two terms in Equation (1) between node i and all of its immediately adjacent nodes. The lumped formulation concentrates the contribution of these terms at node i and therefore on the diagonal of the GWCE system matrix. Our experience utilizing the lumped GWCE formulation indicates that it is more stable but slightly less accurate (primarily in phase propagation) than the consistent formulation as the number of grid points per physical wave length becomes small.

Second, ADCIRC was modified so that the dependent variable computed in the solution of the GWCE is the change in water level from the previous time step $\Delta\zeta^{k+1}$ rather than the water level itself ζ^{k+1}. Thus the time discretized, weak weighted residual representation of the GWCE using the consistent formulation was changed from

$$
\begin{aligned}
&\langle \frac{\zeta^{k+1}-2\zeta^{k}+\zeta^{k-1}}{\Delta t^{2}},\phi_i\rangle_\Omega+\tau_o\langle \frac{\zeta^{k+1}-\zeta^{k-1}}{2\Delta t},\phi_i\rangle_\Omega+\alpha_1\left[\langle gh\frac{\partial\zeta^{k+1}}{\partial x},\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle gh\frac{\partial\zeta^{k+1}}{\partial y},\frac{\partial\phi_i}{\partial y}\rangle_\Omega\right]\\
&+\alpha_2\left[\langle gh\frac{\partial\zeta^{k}}{\partial x},\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle gh\frac{\partial\zeta^{k}}{\partial y},\frac{\partial\phi_i}{\partial y}\rangle_\Omega\right]+\alpha_3\left[\langle gh\frac{\partial\zeta^{k-1}}{\partial x},\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle gh\frac{\partial\zeta^{k-1}}{\partial y},\frac{\partial\phi_i}{\partial y}\rangle_\Omega\right]\\
&=\langle U^k\left(\frac{\zeta^{k}-\zeta^{k-1}}{\Delta t}\right),\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle V^k\left(\frac{\zeta^{k}-\zeta^{k-1}}{\Delta t}\right),\frac{\partial\phi_i}{\partial y}\rangle_\Omega \qquad (3)\\
&-\langle\frac{E_{h2}}{\Delta t}\left(\frac{\partial\zeta^{k}}{\partial x}-\frac{\partial\zeta^{k-1}}{\partial x}\right),\frac{\partial\phi_i}{\partial x}\rangle_\Omega-\langle\frac{E_{h2}}{\Delta t}\left(\frac{\partial\zeta^{k}}{\partial y}-\frac{\partial\zeta^{k-1}}{\partial y}\right),\frac{\partial\phi_i}{\partial y}\rangle_\Omega+\langle W_x^k,\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle W_y^k,\frac{\partial\phi_i}{\partial y}\rangle_\Omega\\
&-\int_{\Gamma_Q}\left(\frac{Q_{n*}^{k+1}-Q_{n*}^{k-1}}{2\Delta t}+\tau_o\alpha_1Q_{n*}^{k+1}+\tau_o\alpha_2Q_{n*}^{k}+\tau_o\alpha_3Q_{n*}^{k-1}\right)\phi_i\,d\Gamma \qquad i=1,\dots.N
\end{aligned}
$$

to

$$
\begin{aligned}
&\langle \frac{\Delta\zeta^{k+1}-\Delta\zeta^{k}}{\Delta t^{2}},\phi_i\rangle_\Omega+\tau_o\langle \frac{\Delta\zeta^{k+1}+\Delta\zeta^{k}}{2\Delta t},\phi_i\rangle_\Omega+\alpha_1\left[\langle gh\frac{\partial\Delta\zeta^{k+1}}{\partial x},\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle gh\frac{\partial\Delta\zeta^{k+1}}{\partial y},\frac{\partial\phi_i}{\partial y}\rangle_\Omega\right]\\
&+(\alpha_1+\alpha_2)\left[\langle gh\frac{\partial\zeta^{k}}{\partial x},\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle gh\frac{\partial\zeta^{k}}{\partial y},\frac{\partial\phi_i}{\partial y}\rangle_\Omega\right]+\alpha_3\left[\langle gh\frac{\partial\zeta^{k-1}}{\partial x},\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle gh\frac{\partial\zeta^{k-1}}{\partial y},\frac{\partial\phi_i}{\partial y}\rangle_\Omega\right]\\
&=\langle U^k\frac{\Delta\zeta^{k}}{\Delta t},\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle V^k\frac{\Delta\zeta^{k}}{\Delta t},\frac{\partial\phi_i}{\partial y}\rangle_\Omega \qquad (4)\\
&-\langle\frac{E_{h2}}{\Delta t}\frac{\partial\Delta\zeta^{k}}{\partial x},\frac{\partial\phi_i}{\partial x}\rangle_\Omega-\langle\frac{E_{h2}}{\Delta t}\frac{\partial\Delta\zeta^{k}}{\partial y},\frac{\partial\phi_i}{\partial y}\rangle_\Omega+\langle W_x^k,\frac{\partial\phi_i}{\partial x}\rangle_\Omega+\langle W_y^k,\frac{\partial\phi_i}{\partial y}\rangle_\Omega\\
&-\int_{\Gamma_Q}\left(\frac{Q_{n*}^{k+1}-Q_{n*}^{k-1}}{2\Delta t}+\tau_o\alpha_1Q_{n*}^{k+1}+\tau_o\alpha_2Q_{n*}^{k}+\tau_o\alpha_3Q_{n*}^{k-1}\right)\phi_i\,d\Gamma \qquad i=1,\dots.N
\end{aligned}
$$

In Equation (4), $\Delta\zeta^{k+1}\equiv\zeta^{k+1}-\zeta^{k}$, $\Delta\zeta^{k}\equiv\zeta^{k}-\zeta^{k-1}$, the superscripts k+1, k and k-1 denote variables evaluated at future, present and past time levels, and all other variables are as defined in Luettich et al. (1992). Once $\Delta\zeta^{k+1}$ is determined, the water level at the new time step is computed from $\zeta^{k+1}=\Delta\zeta^{k+1}+\zeta^{k}$. The change from a matrix solution for ζ^{k+1} to one for $\Delta\zeta^{k+1}$ helps decrease numerical roundoff error and simplifies the model implementation in dry areas.

An analogous change was also made to the lumped formulation of the GWCE.

Third, ADCIRC was modified to include a simple solver for the GWCE for the case of a diagonal system matrix. This occurs if the code is set up to be fully explicit ($\alpha_1 = \alpha_3 = 0$ and $\alpha_2 = 1$) using the lumped formulation. Due to the diagonal GWCE matrix, ADCIRC runs faster and requires less memory in this explicit, lumped mode than in the consistent and/or implicit modes. However, experience indicates that the maximum stable time step using the explicit mode is often about half as large as using the implicit mode.

Forth, ADCIRC was modified to allow the use of a depth dependent drag coefficient:

$$C_f = C_{f\,\min}\left[1 + \left(\frac{H_{break}}{H}\right)^{\theta}\right]^{\gamma/\theta} \tag{5}$$

where C_f is the standard 2D drag coefficient in ADCIRC (applied via either a linear or quadratic friction relationship) and H is the total water depth. This relation has the behavior that C_f approaches $C_{f\,\min}$ in deep water , ($H > H_{break}$), and approaches $C_{f\,\min}\left(H_{break}/H\right)^{\gamma}$ in shallow water, ($H < H_{break}$). The exponent θ determines how rapidly C_f approaches each asymptotic limit and γ determines how rapidly the friction coefficient increases as the water depth decreases. If $C_{f\,\min} \equiv g\,n^2/H_{break}^{\gamma}$ and $\gamma = 1/3$, where g is the gravitational constant and n is the Manning coefficient, Eq. (5) will provide a Manning equation frictional behavior for $H < H_{break}$. Examples of the relationship between $C_{f\,\min}$ and n for $\gamma = 1/3$ are given in Table 1.

Table 1. Comparison between $C_{f\,\min}$ and n if $C_{f\,\min} \equiv g\,n^2/H_{break}^{\gamma}$

$C_{f\,\min}$	n	n	n	n
	H_{break} =1m	H_{break} =5m	H_{break} =10m	H_{break} =20m
0.0015	0.012	0.016	0.018	0.020
0.0020	0.014	0.019	0.021	0.024
0.0025	0.016	0.021	0.023	0.026
0.0030	0.017	0.023	0.025	0.029
0.0040	0.020	0.026	0.030	0.033
0.0050	0.023	0.030	0.033	0.037
0.0100	0.032	0.042	0.047	0.053

WETTING AND DRYING ALGORITHM FOR ADCIRC VERSION 34.XX

The revised wetting and drying algorithm implemented in ADCIRC 34.XX utilizes the modifications described above and retains the elemental approach. This approach assumes that wetting and drying can be represented by turning areas of the grid on and off element by element and is similar to most of the fixed grid wetting and drying schemes that have been implemented in finite difference codes. Conceptually, our algorithm assumes the existence of removable barriers along the sides of all elements in the grid. If all of the nodes making up an element are wet, the barriers on that element are completely removed and the element functions as it would normally, i.e., with no direct influence from wetting and drying. Conversely, all elements connected to a dry node are assumed to have their barriers in place, thereby preventing any flow into or out of these elements. At each dry node, water level is maintained at its value at the time of drying and velocity is set to zero. When an elemental barrier is adjacent to a wet section of the grid, the barrier is treated as a standard land boundary (i.e., a vertical wall against which the water level rises and falls). Either a no normal flux or a no slip condition can be imposed at the barrier, however, the use of a no slip condition considerably simplifies the implementation of the elemental approach and cuts the associated CPU time. Since water depths are expected to be relatively shallow at these nodes, the resulting volumetric transport due to tangential slip would also be small and should not significantly effect the solution. Therefore we have chosen to implement a no slip condition in ADCIRC at all nodes lying along a wet/dry boundary.

As was the case with the previous implementation in ADCIRC, only wetting and drying due to subcritical flow over sloping inclines can realistically be simulated.

The revised wetting and drying algorithm utilizes a nodal array *NODECODE* that has a value at each node of 1 (if the node is wet) or 0 (if the node is dry). An element is wet if the product of the *NODECODE* values for each node in the element is 1 and dry if the product is 0. An additional variable of general importance is the nodal array *NODEREP* that keeps track of the number of time steps since a node last changed state (i.e., changed from wet to dry or dry to wet). Wetting and drying can introduce small oscillations into the solution that cause nodes to repeatedly wet and dry in a nonphysical manner. As described below, *NODEREP* is used to control the frequency with which wetting and drying are allowed to occur and therefore provides some control on this problem.

Checks to determine whether any wetting or drying has occurred are implemented in the time stepping loop after the water level is computed but before velocity is computed. Four basic checks are made in the order that they are described below.

Drying Check 1:

At each wet node in the grid, the total water depth, *H*, is compared with the minimum allowable water depth, *H0*. (*H0* is an input parameter specified in the parameter file (unit 15).) Any node where $H < H0$ is considered to have "dried". Any node where $H < H0/10$ is considered to have "dried severely" and an additional action is taken by raising the water surface elevation at that node so that $H = H0/10$. Any drying specified by this check is overridden at a node if *NODEREP* < *NODEWETMIN* where *NODEWETMIN* is the minimum number of time steps a node must remain wet before it can dry. (*NODEWETMIN* is an input parameter specified in the parameter file (unit 15).)

Wetting Check 1:

Each element that contains one and only one dry node is tested to determine if conditions are favorable for wetting that node. A simple one-dimensional momentum balance between bottom friction and the water surface gradient is constructed along a line connecting one of the wet nodes on the element with the dry node. This is solved to determine the depth-averaged velocity with which water would move between the wet node and the dry node. This calculation is then repeated along a line connecting the other wet node on the element with the dry node to determine the corresponding depth-averaged velocity. The dry node is wetted if either of these depth-averaged velocities is directed toward the dry node and is greater than *VELMIN*, where *VELMIN* is the minimum velocity for wetting. (*VELMIN* is an input parameter specified in the parameter file (unit 15).) Any wetting specified by this check is overridden at a node if *NODEREP* < *NODEDRYMIN* where *NODEDRYMIN* is the minimum number of time steps a node must remain dry before it can wet. (*NODEDRYMIN* is an input parameter specified in the parameter file (unit 15).)

Wetting Check 2:

If an element has a node lying on an internal barrier boundary or a specified discharge boundary that is actively discharging flow into the domain at that node, all nodes in this element must be wet. There is no override for this case.

Drying Check 2:

If a node is connected to only non functioning (dry) elements, the node is considered to be landlocked and dried even though *H > H0.* This check is applied after all other wetting and drying criteria. There is no override for this case.

ACTIVATING WETTING AND DRYING IN ADCIRC VERSION 34.XX

Wetting and drying are activated by setting the variable controlling the nonlinear, finite amplitude terms, *NOLIFA,* to a value of 2 in the parameter file (unit 15). If *NOLIFA* = 2, then *H0, NODEDRYMIN, NODEWETMIN, VELMIN* are read in from the parameter file (unit 15) and used as described above. If *NOLIFA* = 0 or 1, then wetting and drying are not activated. Rather, *H0* is read in from the parameter file (unit 15) and treated as a minimum bathymetric depth. In that case any bathymetric depths in the grid file (unit 14) that are less than *H0* are automatically deepened to be equal to *H0*. If wetting and drying are not activated, *NODEDRYMIN*, *NODEWETMIN*, *VELMIN* are not read in and therefore need not be specified in the parameter file (unit 15).

Values for the parameters controlling wetting and drying will vary from application to application. However, reasonable values might be $H0 = 0.1m$, $NODEDRYMIN = 300/\Delta t$, $NODEWETMIN = 300/\Delta t$, $VELMIN = 0.05\ m/s$, where Δt is the time step in seconds.

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