

Review of wetting and drying algorithms for numerical tidal flow models

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SUMMARY

A review of wetting and drying (WD) algorithms used by contemporary numerical models based on the shallow water equations is presented. The numerical models reviewed employ WD algorithms that fall into four general frameworks: (1) Specifying a thin film of fluid over the entire domain; (2) checking if an element or node is wet, dry or potentially one of the two, and subsequently adding or removing elements from the computational domain; (3) linearly extrapolating the fluid depth onto a dry element and its nodes from nearby wet elements and computing the velocities; and (4) allowing the water surface to extend below the topographic ground surface. This review presents the benefits and drawbacks in terms of accuracy, robustness, computational efficiency, and conservation properties. The WD algorithms also tend to be highly tailored to the numerical model they serve and therefore difficult to generalize. Furthermore, the lack of temporally and spatially defined validation data has hampered comparisons of the models in terms of their ability to simulate WD over real domains. A short discussion of this topic is included in the conclusion. Copyright © 2012 John Wiley & Sons, Ltd.

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1. INTRODUCTION

In coastal regions worldwide, the flooding and ebbing of the tide is the primary driver of the local ecosystem. All life adapts to its cyclical rhythm. Estuarine plant life naturally migrates to those areas that meet its specific and narrow tolerances for inundation, salinity, and soil type [1]. Fauna follows shortly behind because it adapts to the patterns dictated by its food sources. These ecological patterns unique to the coast are defined by the behavior of the tides.

The incoming tide (commonly referred to as the flood tide) progressively raises the water level at the coastline and in tidal creeks causing them to overflow into the surrounding tidal marshes. Water levels continue to rise towards a peak at which time flows in the tidal creeks are at their minimum (known as slack tide). After water levels peak, they steadily fall draining the surrounding tidal marshes and exit through tidal creeks (known as ebb tide). The duration of inundation (known as the hydroperiod) is unique to each coastal region, particularly within tidal creek and salt marsh systems, and defines the local characteristics of the ecosystem. The hydroperiod, controlled by the regularity of the tides, can also be influenced by external factors including freshwater inflows and meteorological conditions such as wind and pressure (especially during extreme events such as hurricanes).

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An additional influencing (complicating) factor is sea level rise [1]. However, the incorporation of sea level rise into coastal models extends beyond simply raising present-day model results as an approximation of increased water surface elevations. Instead, the water surface time series resulting from the tides, river inflow, meteorological effects (storm surge), or any other forcing mechanism is dynamically affected by sea level rise [2]. Sea level rise raises baseline water levels and introduces entirely new bathymetry to the flow. This new bathymetry substantially influences the flow conditions.

The complex physical process of an advancing or receding flood wave presents a nontrivial modeling challenge. As a flood wave inundates a previously dry area, the model must adapt to include these now wet areas into the model. Shortly thereafter, especially in the case of tidal flow modeling, the model must then simulate the receding flood by drying these elements and therefore removing them from the computations. Depending on the scheme, these additions or removals from the computations may be explicit, that is, elements are literally activated (wetted) or deactivated (dried) within the computational matrix, or implicit, that is, the dry elements are flagged as 'dry' but contain a virtual water level and are still included in the computations. To date, a broad scope review of existing algorithms for addressing the wetting and drying (WD) problem in tidal flow and storm surge inundation modeling has not been conducted.

The issue of WD capability is important to the end-user of any given model because inundation extent and water level provide crucial information to stakeholders, managers, and emergency personnel in coastal areas. In the case of storm surge inundation extent, a process that is highly dependent on topography [3], an accurate prediction is crucial to justify selection of evacuation areas and routes. Another coastal process where an understanding of the wetting front propagation is crucial is the cyclical flooding and ebbing of tidal marshes. The complex ecology of these intertidal zones is highly dependent on a delicate balance of processes simulated by WD algorithms: inundation extent and duration (hydroperiod), and the transport of sediment and nutrients [4,5]. The transport of sediment and contaminants is its own specialized modeling field within the study of coastal and riverine processes. Because the fluid is the medium in which both sediments and contaminants are transported, its spatial extent plays a crucial role in the determination of the fate of these constituents. In fact, it is essential that wetting and drying be incorporated into any model seeking to model these processes in environments with moving flow boundaries, such as tidal environments [6, 7]. Furthermore, on a more fundamental level, WD is essential to the computation of tidal datums such as mean sea level, mean low water, and mean high water [8]. It has been shown that these datums vary spatially according to local flow conditions, especially within shallow coastal environments [9, 10]. Accurate simulation of WD processes allows researchers to derive these tidal datums that are used heavily for mapping and navigation and modeling applications [11].

A variety of numerical models have been developed to simulate coastal hydrodynamics in one, two, and three dimensions. These models employ a diverse set of techniques for solving the governing equations, discretizing the domain, and marching forward in time. The numerical schemes employed in some widely used models can be found in [12–18], with particular emphasis on the shallow water equations. Although there is great interest in the formulations and discretizations of the shallow water equations, this paper focuses on another aspect of the overall solution algorithm: wetting and drying of computational elements and nodes.

In general, a typical coastal and estuarine hydrodynamic model solves the governing equations over the entire model domain at each time step. However, the equations only apply to those computational elements where a fluid (water) is present. Thus, the handling of an element's wet or dry state performs the crucial duty of indicating how or if it is to be included in the computations at the present time step. Figure 1 depicts the problem in graphical form for a case with a triangular element spatial discretization. As shown, the WD algorithm is tasked with representing the wetting front within the constraints of the mesh resolution. Various algorithms using unique tactics have been set forth to accomplish this; those with application to tidal circulation modeling will be described in this paper.

Accurately capturing the physics of the inundation / recession process has historically been addressed as a computational (WD) problem, to be solved with an algorithm implemented in the computer code and executed in run time. This problem is unique in that it involves a delicate balance of computational efficiency (both processing demand and memory allocation), numerical

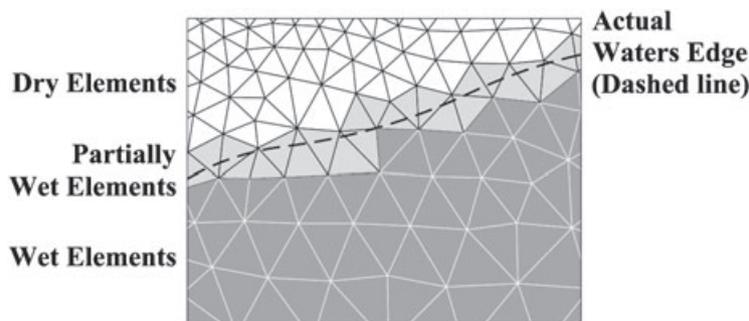


Figure 1. Unstructured triangular mesh illustrating wetting front in reality and as seen by numerical model.

stability (convergence, spurious oscillations), and scientific accuracy. As with any computer modeling technique, the closer the solution describes the physics, the more computationally intensive it is. Previous reviews of WD algorithms have stressed the computational solutions to the issue, rather than the capture of the physical processes involved [19]. As stated above, implementing a numerically stable solution that does not introduce spurious noise into the results is indeed important; however, a purely computational remedy that is based loosely or not at all on the physics has the potential to induce artificial damping or dissipation of solution fluctuations. Tchamen and Kahawita [20] provided an excellent description of the problems faced by model developers and the generic algorithm used to address them. Balzano [21] evaluated seven WD schemes implemented in the same model, analyzed the shortcomings evident in the one-dimensional test cases, and proposed three new schemes. D'Alpaos and Defina [19] also presented a general review of WD algorithms as a foundation to their set of two-dimensional shallow flow equations modified to handle partially wet elements [22].

This paper presents a review of WD algorithms in popular coastal and estuarine models based on the shallow water equations. This review is different in scope from previous reviews (listed above) in that the focus is on models typically used to model tidal hydrodynamics and storm surge in contemporary studies. Although Balzano [21] presented a review of WD algorithms in use from 1968–1993, and D'Alpaos and Defina [19] included more current schemes, a comprehensive review and characterization of contemporary WD algorithms has not been carried out. The models reviewed all operate on structured or unstructured numerical grids that are temporally and spatially constant (i.e. fixed). For the purposes of this paper, moving grid boundary [23–25] and adaptive mesh-generation / advancing front [26, 27] approaches are not considered. Although highly suited to the problem of wetting and drying, they are omitted here in favor of models that are more commonly applied to tidal circulation modeling. An outcome from this review is a categorization of WD algorithms. Thus, the paper is structured around the four categories identified in the review (please refer to Figure 2 for illustrations of these groups): (i) those that specify a thin film of fluid over the entire domain to compute the equations of mass and momentum conservation over the entire domain at every time step; (ii) those that employ checking routines to determine if an element or node is wet, dry or potentially one of the two, subsequently removing dry elements from the computational domain; (iii) those that extrapolate the fluid depth from wet nodes onto dry nodes and compute the velocities in the newly wet element; and (iv) those that allow the model to tolerate negative water depths and permit the simulated water surface to extend below ground. Special emphasis is given to each category's application to specific numeric schemes, namely finite difference (FD), finite element (FE), and finite volume (FV) methods along with their performance in conserving mass and capturing the relevant physics such as the advance and recession of the wetting front. Lastly, a summary is presented along with a brief discussion of future research related to this topic.

2. THIN FILM ALGORITHMS

As stated previously, thin film algorithms specify a viscous sublayer of fluid over the entire computational domain. This allows all nodes, elements, and cells to be included in the computational

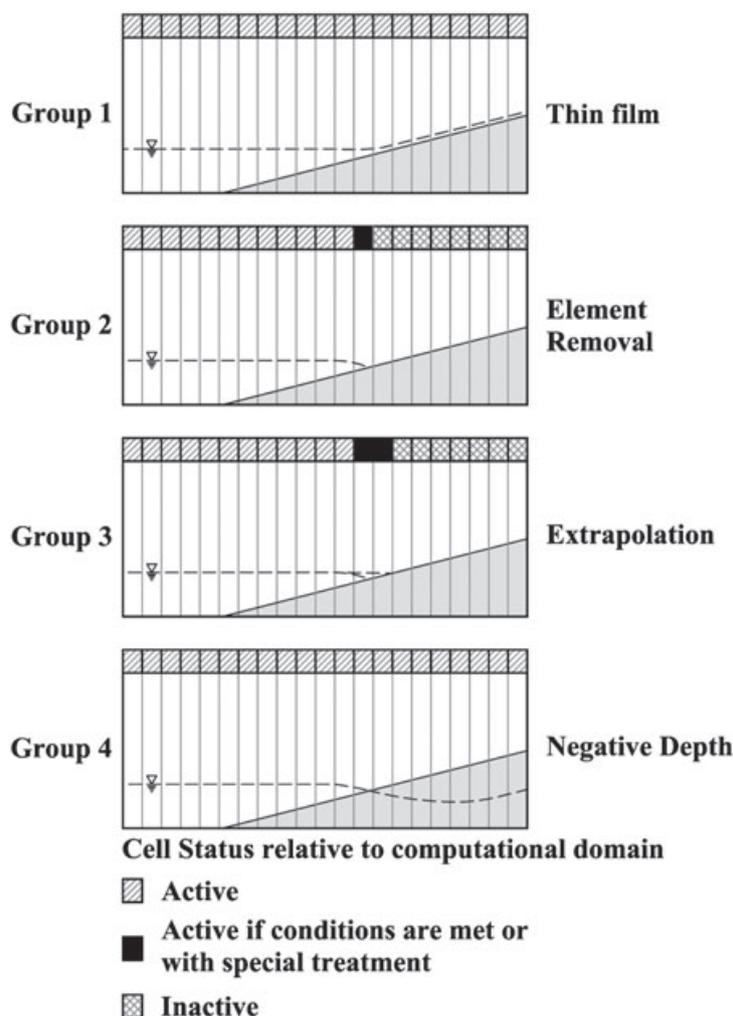


Figure 2. Illustration of the four categories of wetting and drying algorithms.

domain at each time step. There is typically a minimum threshold depth that defines the categories of wet or dry in the model, even though there is some fluid present over the entire domain. In some cases, these algorithms employ techniques similar to those of element removal algorithms. However, the manner of the constant presence of some fluid in every element within the domain is their defining feature. Please refer to Figure 2, Group 1.

In developing their two-dimensional finite element model for river floodplain inundation, Bates and Anderson [28] applied a modified form of the WD scheme proposed by King and Roig [29]. This scheme operated on a fixed mesh and applied a coefficient θ to represent the portion of an element available for flow. This enabled the model to include partially wet elements in the computations and ensured smooth transitions from wet to dry and vice-versa. To overcome numerical difficulties (namely undefined derivatives and discontinuities resulting from zero water depths) in the solution procedure, a small, positive θ_{\min} value was incorporated and represented effectively dry conditions. This model conserves mass globally, that is, at the domain boundaries and is shown to conserve mass locally to within $\pm 2\%$. In the test cases presented, the model appears to produce realistic, smooth, and continuous representations of the wetting front.

As explained by Oey [30], the Princeton Ocean Model [POM; 18, 31] utilized a variety of approaches to implement WD into their finite difference model. First, a boundary was defined over which water can never flow, that is, the cells landward of this boundary must always be dry. Then a region seaward of this boundary was defined where cells can be either wet or dry. This region

was intended to simulate marsh and tidal flat areas. In this wet or dry region, cells were defined with a small film of water called with depth H_{dry} (stated as 5 cm) in which the equations of mass and momentum conservation could be solved. The resulting depths were then checked at each cell interface; if the depth dropped below H_{dry} then the velocity was set to zero and the wet or dry state was updated for the next time step. This is one of the simpler, more robust schemes employed; however, it falls into the category of algorithms that require a nonzero depth in every cell, thus solving the equations for all cells at each time step. Xie *et al.* [32] thoroughly explained this algorithm and applied it to an idealized test case.

In the framework of a one-dimensional discontinuous Galerkin (DG) finite element discretization, Bokhove [33] presented a WD scheme that sought to preserve the water depth as a positive value. In this model, the WD scheme permitted isolated patches of wet or dry areas, even those that are generated during a simulation such as waves overtopping a dike. To resolve discontinuities generated by dry patches that emerge in flat topography such as the recession of water on a tidal flat, the model splits the cells near the boundary. WD algorithms of this type in DG models have also been studied by Ambati [34]. Bunya *et al.* [35] also developed a WD scheme for a DG shallow water equations model. Similarly, they sought to maintain a positive water depth in the elements and strictly prohibited flux between adjacent dry elements.

Lastly, FVCOM [13, 36] is a finite volume coastal ocean model. The WD algorithm is described as a point treatment incorporating a viscous sublayer of specified thickness (to avoid zero depth and the resulting singularity). The water depth at the nodes is checked against the thickness of the viscous sublayer to determine their state as wet or dry. The cells are subjected to a similar check that incorporates all nodes associated with the cell. If the depth in a cell is less than the thickness of the viscous sublayer, the velocity is set to zero and the cell is subsequently removed from transport computations as well [37]. FVCOM has been used in WD applications ranging from storm surge [38, 39] to wetland-estuarine-shelf interactions in Massachusetts [40].

3. ELEMENT REMOVAL ALGORITHMS

Element removal algorithms employ unique (to each model) systems of checks to determine if a cell or element is wet, dry, or partially wet. The wet elements are included in the computational domain and the dry ones are not. However, in the case of partially wet elements, further consideration is necessary to determine if the flow conditions at the wetting front are capable of fully wetting a partially wet element. As explained in the examples below, each model approaches this task in a specific manner. Please refer to Figure 2, Group 2 for an illustration of this algorithm.

Modifying the earlier model of Falconer and Chen [41], Lin *et al.* [25] implemented a WD scheme in their three-dimensional finite difference model. During each time step, a series of drying and flooding checks was performed to determine whether or not to include a particular grid cell in the computational domain. The drying checks were based on a length scale that describes the bed roughness and were used to determine if a grid cell should be removed from the computational domain by examining the depths at the cell center and each side. To determine if a dry cell is flooded and should be returned to the computational domain, the length scale was used again in comparison with the depths of surrounding grid cells to determine if conditions warrant the flooding of the cell. If so, the cell was returned to the computational domain at the start of the next half time step. The method was validated and tested on an idealized flat tidal bed, an idealized rectangular harbor, and in the Humbert Estuary on the northeast coast of England.

In developing their finite difference storm surge inundation model, Hubbert and McInnes [42] employed a WD scheme designed to produce smoothly varying results at the wetting front. As in typical WD schemes, the water level in adjacent wet cells determines if a dry cell is eligible to become wet. However, the authors also calculated the potential length of travel of the wetting front in one time step by observing the current velocity in the wet cells. For a dry cell to become wet, the water level and the current velocity in the adjacent wet cell must warrant it. The scheme was also applied to the drying of flooded cells. This WD scheme was tested on two inundation scenarios in Australia. By varying the grid resolution of the models, the authors showed the danger in artificially

wetting dry cells based on water depth criteria alone. In their test cases, large grid cells caused the wetting front to propagate inland beyond a realistic extent when the grid cells were declared wet without the support of the current velocity criteria.

Bates and Hervouet [43] utilized the finite element model TELEMAC-2D [15, 44] and began the WD process by characterizing all elements as one of four types: fully wet, fully dry, partly wet (dam-break type), and partly wet (flooding type). This categorization allowed them to apply an appropriate mass and momentum correction scheme. Once the element subtype was established, all partially wet elements were included in the computations and steps were taken to correct the mass and momentum discrepancies. In the case of momentum, the authors applied the scheme of Hervouet and Janin [45], which assumed that the change in velocity with respect to time is equal to the water surface slope times the acceleration because of gravity. In some cases, this resulted in spurious results when the water surface slope was nearly flat, such as in the case of an element flooding from the bottom up. In terms of mass conservation, Bates and Hervouet [43] applied the scheme of Defina *et al.* [46]. This scheme utilizes the bottom topography and water surface elevation to calculate a scaling factor that is applied to the continuity equation. This scaling factor allows for a true representation of the volume of water present on the element. Tests of this method for the simple case of a sinusoidal wave on a sloping beach were presented by Bates [47]. Carniello *et al.* [48] also employed this scheme in their model of the Venice lagoon in Italy. However, in addition to simulating WD, they coupled their model to a finite volume wind wave model to simulate the combined effects of waves and tide propagation. Defina [22] referenced and built on this approach by modifying the two-dimensional flow (momentum and continuity) equations to accommodate partially wet elements. The same scaling factor was applied to the continuity equation to preserve mass conservation. The momentum equations were derived to account for the subgrid topographic irregularities present in most models and the volume of water (and the subsequent change in water volume) in those elements.

Casulli and Walters [49] allowed their three-dimensional finite difference / finite volume scheme to incorporate WD 'in a natural and straightforward manner [49],' typical of kinetic finite volume models. When the water depths were calculated at each time step, the vertical grid spacing was updated accordingly. If the water depth was zero, then the height of the faces and subsequently the velocity through the faces was also set to zero. Because of the finite volume discretization of the free surface equation, mass is conserved both locally and globally. This was based on earlier work by Casulli and Cheng [50] and also utilized by Zhang *et al.* [51] in the development of their ELCIRC model. Although the execution of WD algorithms such as the kinetic energy criteria employed by Lu [52] and the wet-dry tolerance parameter employed by Cea *et al.* [53] in this case are innovative in their determination of an element's state, they should still be classified as element removal algorithms.

Ji *et al.* [54] used the Environmental Fluid Dynamics Code [EFDC; 55] and employed the WD scheme presented by Hamrick [56] in their analysis of the flooding and drying behavior of Morro Bay, California. As with most finite difference and finite volume models, the key to the WD scheme was the determination of whether or not a cell face was dry based on the water depth in the cell. If a cell face was determined to be dry, the flux was forced to zero.

In Japan, Matsumoto *et al.* [57] applied a WD approach in their finite element model that used the bubble function [58] for discretization in space and the least-squares bubble function for discretization in time. They employed the minimum depth criteria to determine whether or not (and how) an element is included in the computations. It was shown to work well as demonstrated in a one-dimensional dam break test case and also a two-dimensional simulation of flow in the Nagaragawa River, Japan.

The finite volume model proposed by Brufau *et al.* [12] employed a scheme where the wetting front was treated as a boundary where the flow of water was controlled by the difference in both water depth and bottom elevation. To maintain mass conservation, the difference in bottom elevation was locally redefined to maintain equilibrium. One special case discussed by the authors was the propagation of the wetting front on a dry, adverse slope. In this case, the velocity across the wet/dry cell interface needed to be set to zero or there was a risk of artificially wetting the higher dry cell as a result of the locally redefined bottom elevation difference.

To simulate the Quoddy region in the Bay of Fundy, Greenberg *et al.* [59] adapted the three-dimensional finite element QUODDY model [60] to implement a WD scheme. The scheme integrated into the QUODDY model was a relatively simple dry element removal scheme. The model checked the depth at each node of an element and if they were below a certain threshold, the element was considered dry and the velocity at the bottom was set to zero. The authors ran an experiment on an idealized mesh before testing the adapted QUODDY code, termed QUODDY_dry, to the Quoddy region where it proved itself to be a useful tool. (Note: as shown in the above citations, the model was named QUODDY prior to its application in the Quoddy region in the Bay of Fundy.)

One of the most commonly used codes in tidal circulation modeling, the Advanced Circulation (ADCIRC) finite element model [16, 17, 61] employs a WD algorithm that makes cells active or inactive if the depth exceeds a certain minimum threshold. Dietrich *et al.* [62] thoroughly explained the evolution of the ADCIRC WD algorithm; only relevant details are presented here. In its first WD algorithm, ADCIRC performed a depth check at each node; if the depth exceeded the minimum threshold depth, the node was activated and participated in the computations. Otherwise, the node was deemed dry and was removed from the computations. In this algorithm there was also a criteria imposed that dictated a node was to remain in its current state for a specified number of time steps before it was allowed to change state. This was implemented in an effort to avoid spurious noise resulting from thin layers of water at or near the threshold depth for rapidly switching a node between wet and dry states [63, 64]. Minor updates to this algorithm were introduced in 1999 and included a node state variable (1 for wet, 0 for dry) and also some elemental wetting and drying checks were implemented to determine the best method for modifying the node state based on elemental conditions such as the number of wet nodes in the element and whether or not bottom friction or presence of barriers would inhibit the wetting of nodes [65]. A subsequent revision in 2004 eliminated the condition that the node must remain in its current state for a specified number of time steps and also addressed the issue of thin films of water creating mass balance errors on steep slopes. The node state condition was determined to be the cause of abnormally slow propagation of flood waves over flat floodplains (a common situation in hurricane storm surge simulations). A new parameter was introduced that forced water to accumulate on a slope prior to flowing. This parameter was applied at the down gradient node within an element and was set to be 120% of the minimum depth threshold that determines if an element is wet. The 120% value was stated as being an ad hoc selection that had performed well in tests. If the down gradient node had a depth less than this new parameter, then the entire element was declared dry. This new algorithm was determined to perform satisfactorily in test cases, increasing model stability to the point of allowing the time step to double [62].

Le Dissez *et al.* [66] proposed a new finite volume hydrodynamic model in which the WD was handled by incorporating a Darcy term into the Navier–Stokes equations along with a phase function C . The phase function varied in time according to the prevailing flow conditions. The implementation of the Darcy term was essentially a penalty method [67] that was turned on and off by a coefficient value K representing porosity of the element or cell. The value of K (and thus the activation of the Darcy term) was controlled by the phase function (i.e. if $C = 1$, then K is sufficiently small to make the cell impermeable; if $C < 1$, then K is sufficiently large to allow flow into the cell). This approach was shown to work well on both a series of one-dimensional test cases along with a tidal simulation of the Arcachon lagoon. The results showed good agreement with accepted model results that had been validated against field measurements.

Delft3D-FLOW [14] is a finite difference model commonly used in consulting projects worldwide. Its WD scheme is typical of finite difference models in that a series of checks are performed to determine if a grid point is wet or dry based on the depth of water relative to a threshold value specified by the user. If it is wet, it is included in the computations; if it is dry, it is not. If the water depth at a cell face drops below the threshold (or a specified fraction of the threshold) then the velocity across that face is set to zero and no momentum or mass transfer occurs. This system, while simple, is robust and effective. Vatvani *et al.* [68] provided a summary of the WD scheme in Delft3D along with their case study of the Bay of Bengal, India.

Another finite difference model commonly used in consulting and research projects is MIKE 21 developed by Danish Hydraulic Institute (DHI) [69]. This software operates on a rectangular grid and somewhat uniquely specifies two separate flooding and drying depth criteria. This allows the user to specify one coefficient that establishes when a cell is considered flooded (and added to the computations) and another coefficient for when a cell is considered dried (and removed from the computations). The recommended values for the flooding and drying depth criteria 0.2 to 0.4 m and 0.1 to 0.2 m, respectively with a recommended difference between the two parameters of 0.1 m [69]. Bekic *et al.* [70] modified these parameters to calibrate their model of the Clyde Estuary in Glasgow, Scotland. MIKE 21 has also been used in many flooding and drying applications including the Bay of Bengal [71], Mele Bay and Port Vila in Vanuatu [72], and Oualidia Lagoon in Morocco [73].

In addition to studies of coastal and estuarine circulation, WD schemes have also been applied to wave overtopping models such as Hu *et al.* [74]. In this case, a one-dimensional model was developed to simulate wave propagation and overtopping over idealized cases such as steps and sloping beaches and common coastal structures such as seawalls (sloping, vertical rock armored). Similar to circulation models, minimum wetting depths along with minimum friction depths (i.e., the minimum depth used to calculate friction losses) were employed to control WD.

4. DEPTH EXTRAPOLATION ALGORITHMS

For this set of algorithms, the conditions at the wetting front are given special consideration and play the vital role in advancing the water's edge in the model. In most cases, the depth is extrapolated from wet cells onto dry cells if the conditions warrant. An example of the conditions being too restrictive to allow this is an area where the bottom friction coefficient prevents the advancement of low energy flows. If the depth is able to be extrapolated from a wet cell onto a dry cell, then these new depths are used to compute velocities and the elements or cells are now part of the wet domain (until they become dry, that is). Please refer to Figure 2, Group 3 for an illustration of this algorithm.

Lynett *et al.* [75] used linear extrapolation from the wet region into the dry in the WD scheme of their finite difference model designed to simulate wave runoff. The extrapolation process proceeded by locating and analyzing the boundary area between the wet and dry regions. The free surface in the dry region was estimated using one-dimensional linear interpolation and averaging. The interpolation then proceeded to the next level of dry cells, based on the first level of interpolated values in formerly dry cells. The only situation this scheme could not address was a wet region surrounded by dry cells. In this case, the wet area was removed from the computational domain and its water levels were linearly extrapolated as well. This method was validated in both the one-dimensional and two-dimensional spaces using an idealized domain and sinusoidal wave forcing.

In the development of their shallow water flooding model, Bradford and Sanders [76] sought to overcome the limitations of the contemporary WD schemes employed in finite volume methods. To address the problem of numerical instabilities generated by very small depths in a partially wet cell as a result of the averaging of depths from wet and dry nodes, a depth tolerance value ε was defined; velocities were only calculated if the depth exceeded this tolerance. This issue was of particular importance in terms of model sensitivity when the bed friction was parameterized using Manning's n . The issue of averaging the depths at the nodes of a partially wet cell also caused artificial leakage into adjacent cells by unrealistically wetting cell faces. This issue was resolved by extrapolating the elevation of the free surface from the neighboring fully wet cell. Lastly, spurious water movement can be induced in cells with sloping bed topographies. To manage this condition, the model did not solve the momentum equations in partially wet cells but rather extrapolated the velocity from the neighboring fully wet cell with the largest water depth.

Begnudelli and Sanders [77] proposed a geometric method for WD in their finite volume model. They stated that because the finite volume model uses the average depth in a cell applied at the centroid to indicate water volume, this could lead to errors particularly over irregular topography. For example, it is possible that the free surface elevation can be below the topographic elevation of the centroid. To deal with this, they proposed the volume/free-surface relationships (VFR) method to model partially wet cells that differentiated between the free surface elevation and the depth at the centroid. VFRs calculated the elevation of the free surface or average depth (depending on the

solution mode, either forward or inverse) after determining the number of wet nodes (for triangular elements, this can be zero, one, two or three). This approach was tested in the aforementioned paper and also applied in future modeling studies conducted in [78–82]. Please note that the operational version of this model is known as BreZo.

5. NEGATIVE DEPTH ALGORITHMS

Negative depth algorithms are closely aligned with porosity schemes. In these cases, the water surface exists below the ground surface, allowing the governing equations to be computed over the entire domain. Areas with negative depths are considered dry. The subsurface flow conditions are controlled with porosity terms. As the flow depth increases and eventually becomes positive, the wetting of dry cells is simulated. Please refer to Figure 2, Group 4 for an illustration of this concept.

Heniche *et al.* [83] created a WD scheme that relied on the natural extent of the wetting front, that is, the natural edge where the water surface intersects with the ground surface, a concept that can be easily visualized in a realistic sense. However, the WD scheme in this finite element model allowed the water surface to plunge beneath the topographic surface producing negative water depths. The computations were allowed to proceed by imposing a high friction coefficient in dry areas (i.e., cells with a negative depth), effectively preventing current velocities. In the end, the three test cases proved that mass and momentum are fully conserved in situations of relatively slow and stable wetting front propagation. The authors did concede that this scheme was not well suited to dam break problems.

Using a similar WD concept and the finite element model RMA2 [84], Nielsen and Apelt [85] described the class of WD algorithms known as ‘thin slot’, in particular the form known as marsh porosity. In this WD scheme, flow was allowed to plunge beneath the surface and flow in a low porosity medium. Mass conservation was maintained by transforming the water depth to an equivalent depth. This scheme, applied to four test cases, shows that the selection of WD parameters heavily influences the results.

Similarly to the marsh porosity method, Jiang and Wai [86] employed a scheme known as the capillary method to their three-dimensional finite element model. This scheme implements a network of capillaries that connect dry cells together just below the minimum water level (i.e., the capillaries are always wet.) This enables the water surface in a dry cell to vary naturally along with that of the nearby wet cells through a modification of the continuity equation but not the momentum equations. Therefore, mass is conserved through the capillaries and because the momentum equations only act on wet cells, momentum is conserved as well. This particular formulation shows great potential in simulating tidal recession from coastal marshes and tidal flats that tend to leave behind wet pools. The method was tested in an idealized case of a basin with varying slopes similar to that of Leclerc *et al.* [87] and also a real application to the Xiamen Estuary in China.

Although TELEMAC-2D was previously listed as utilizing an element removal algorithm, newer versions also employ a negative depth scheme [88, 89] with a multitude of options for treating negative depths as they occur including smoothing, establishing a threshold parameter for smoothing, and ensuring positivity.

6. DISCUSSION

A variety of schemes have been developed to address WD in coastal hydrodynamic model formulations and codes. A summary of the WD algorithms is presented in Table I and could serve as a quick reference to a practicing modeler seeking to determine which model (or WD algorithm) to apply to a given research project. The columns represent the most important facets of a WD algorithm from the point of view of a coastal modeler: What popular models use this type of WD algorithm? What numerical schemes employ this type of WD algorithm? How well does it conserve mass globally and locally? How well does it capture the fundamental physics of an advancing/receding wetting front?

Those that specify a thin film of fluid over the entire domain to compute the equations of mass and momentum conservation over the entire domain at every time step are computationally more

Table I. Summary of WD algorithm categories.

Algorithm category	Examples	Numerical scheme applications	Mass conservation	Physics capture
Thin film	POM FVCOM	FE, FV	Adequate, but requires correction after water levels are computed.	Alters the nature of the physics by having thin layer of fluid on 'dry' cells, however it produces smooth and realistic wetting fronts.
Element removal	TELEMAC-2D EFDC ADCIRC Delft3D-FLOW MIKE 21	FE, FD, FV	Dependent on model. Most models conserve mass globally. Newer models using FE Discontinuous Galerkin approach conserve mass locally.	Excellent because of subgrid correction schemes. Tend to perform better on advancing wetting fronts than receding.
Depth extrapolation	BreZo	FD, FV	Generally yes, with correction procedures required in most cases.	Very good in a wide variety of flow scenarios because of advanced correction schemes such as VFR.
Negative depth	RMA2	FE	Conserves well on slow moving fronts. Performance dependent on specification of WD parameters.	Same as mass conservation.

expensive but generally conserve mass and momentum with little or no correction. They also tend to produce smooth solutions at the wetting front. However, this is all predicated on the fact that a fictitious layer of fluid exists over the entire domain, or in the case of some hybrid algorithms, those regions that are eligible to wet and dry. Whether or not this can be classified as truly 'capturing the physics' is a matter of perspective.

Algorithms that employ checking routines to determine if an element or node is wet, dry or potentially one of the two and subsequently removing dry elements from the computational domain are the most common and employed in finite difference, finite element, and finite volume models. Algorithms of this type save computational cost by not operating on the entire domain at each time step; however, issues concerning the rapid toggling on or off of elements as they become wet or dry near the wetting front and accelerating or dampening the overland flood wave propagation (especially in flat areas) has been an issue, especially in models with implicit solvers. This can be overcome by increasing the spatial resolution of the mesh or by reducing the time step. Furthermore, implementing an explicit solver can also reduce spurious noise at the wetting front. Also, the implementation of DG basis functions within finite element models enforces local mass conservation and produces excellent solutions (although more costly computationally) in a wide variety of problems ranging from bottom up flooding to dam-break scenarios.

Algorithms that extrapolate the fluid depth from wet nodes onto dry nodes and compute the velocities in the newly wet element tend to produce very smooth solutions at the wetting front. However, this occasionally comes at the expense of artificially wetting dry elements, a problem that is managed by subalgorithms such as volume/free-surface relationship (VFR) [77]. Extrapolation schemes tend to be used almost exclusively by finite volume models. Mass is conserved using correction schemes because clearly the extrapolation of the water surface introduces new mass into the system. However, the magnitude of this increase is commensurate with that which would exist in reality under the given circumstances; therefore, one can state that the scheme realistically conserves mass.

Lastly, WD algorithms that allow the model to tolerate negative water depths and permit the simulated water surface to extend below ground tend to be used exclusively in finite element models. This category of WD algorithms most closely captures the actual physical processes at work because the wetting front does in fact penetrate the ground surface in reality. Also, no mass is ever artificially

introduced into the system (as in thin film and depth extrapolation type algorithms). The implementation of the porosity (both above and below the ground surface) concept shows particular promise in modeling the wetting front in a most natural and intuitive manner.

When discussing the capture of physics, it is essential to make a distinction between a mathematically rigorous treatment of the processes within the model and the smoothness, continuity and realistic appearance of the results. Mathematically rigorous schemes often require damping of numerical instabilities during run-time to produce a usable solution. On the other hand, schemes that are more loosely based on the physics tend to produce more natural and realistic looking results. It is up to the modeler to apply his/her judgment in selecting a WD scheme to meet their individual needs and the needs of their project. To that end, more rigorous comparison testing of WD algorithms is required.

To facilitate the aforementioned rigorous model testing, accurate benchmark data from reproducible real world events is necessary. This will enable direct, measurable performance tests of a particular model's ability to simulate wetting and drying. Furthermore, it will provide crucial information that will allow WD algorithm developers to correct, refine, and establish the scope and applicability of their schemes for real world applications. However, at the present time, these types of data are scarce. High water marks generated during an inundation event and documented after the storm passes are typically readily available but require significant quality control because many factors including meteorological conditions, wind wave influences and human error often negatively impacts the accuracy of these data. Furthermore, they have no time signature and therefore serve only to validate the model in a peak water level context with no indication of the performance of the WD algorithm. Water level time series data are also readily available, but typically only located at established river gauge stations or offshore buoys. This prevents them from assessing how well a model captures the progression of the wetting front because their water level measurements secondarily rely on the topography data to infer the extent of inundation. The most beneficial benchmark data to measure the WD performance of a model would be spatially-accurate time-stamped inundation extents. The development of methods to generate these benchmark data is addressed briefly in the conclusion.

7. CONCLUSIONS AND FUTURE RESEARCH

Wetting and drying algorithms are important to the accurate and useful simulation of overland flooding and inundation. WD is still a nontrivial challenge to numerical modelers in that oftentimes stable, smoothly varying solutions prove to be inaccurate and accurate solutions require very high spatial and temporal resolutions that are computationally costly and frequently unstable. The review conducted herein determined that WD algorithms generally fall into one of four categories: (i) thin film algorithms; (ii) element removal algorithms; (iii) depth extrapolation algorithms; and (iv) negative depth algorithms. Each scheme has benefits and drawbacks in terms of its applicability to a variety of models, mass conservation both locally and globally, and the capture of the physics.

Although this paper only presents a review of WD algorithms currently and formerly in use, it could also serve as a starting point for a qualitative comparison between models in terms of their ability to simulate WD over a real domain. This task is nontrivial in that it requires testing of the numerical efficiency of the method and its ability to accurately simulate the movement of the wetting front [87]. A study of this type could begin with a comparison of model performance in a still water test for stability such as Liang and Marche [90], proceed to synthetic test cases for which there are analytical solutions such as the parabolic bowl test case [91], Leclerc test case [87] or the quarter-annular harbor [92], and conclude with a series of real world scenarios. The latter test requires benchmark data sets that are both temporally and spatially defined. In the case of shallow water equation models, a spatial data set depicting the extent of the inundated area at a particular time would be invaluable. Research into using remotely sensed data to provide this type of benchmark data has been conducted by Richards *et al.* [93], Hess *et al.* [94], Smith [95], Horritt [96], and Chaouch *et al.* [97], and has been put into practice by Cobby *et al.* [98], Mason *et al.* [99], and Oey *et al.* [100].

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