Using WASH123D to Design Spreader Canals for Water Management in Watersheds

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Abstract

In the federally approved Comprehensive Everglades Restoration Plan (CERP, http://www.evergladesplan.org/), the restoration of the South Florida ecosystem is a major task for the U.S. Army Corps of Engineers and the South Florida Water Management District. Many competing entities have an interest in the restoration process which will probably include physical changes to the land surface and adjustments to water deliveries. The Biscayne Bay Coastal Wetlands (BBCW) Project is one component of more than 60 restoration plans and has a goal to restore or enhance freshwater wetlands, tidal wetlands, and near shore bay habitat. In an effort to restore wetlands, several structures, and management plans and scenarios are considered. One of the plans is to deliver fresh water from the existing canals through a shallow spreader canal system that is to distribute fresh water through wetlands into the Biscayne Bay. To achieve this, a tool is needed to design this complicated shallow spreader canal system. This paper presents how a spreader canal system, which includes 1D canal network routing, 2D overland flow, 3D subsurface flow, and flow through the interface of any two sub-domains of the spreader canal system, is simulated with the WASH123D computer code. A brief description of the model will be given. A hypothetical example that includes two cases and uses topographic data and a high-resolution computational mesh for one project area will be considered to demonstrate how WASH123D can help design a spreader canal system. A couple of issues concerning run time and numerical convergence of the coupled flow model will also be discussed in this paper.

Background

The Biscayne Bay Coastal Wetlands (BBCW) Project is one component of the more than 60 restoration plans and has a goal to restore the coastal wetlands area in Central and South Biscayne Bay along its western shoreline. In the existing condition, fresh water

plumes emanating from the mouths of canals and well-defined ditches can create local freshening of Biscayne Bay that can be harmful to sea grasses and the ecology of Biscayne Bay. Current restoration efforts in southern Florida are examining alternative water management plans that could change the quantity and the timing (Q & T) of freshwater delivery to the bay by restoring coastal wetlands along its western shoreline of the Biscayne Bay. In contrast to these well-defined surface features, shallow water wetlands can diffuse the introduction of fresh water into Biscayne Bay. Using wetlands to recharge fresh water into the groundwater system can be useful to minimize fresh water plumes extending into Biscayne Bay and to help minimize and/or impede saltwater intrusion. One scenario to address this effort is to create a spreader canal system to redistribute available surface water entering the area from the regional canal system. The spreader canal system would consist of a delivery canal and shallow swales (i.e., spreader canals) where water flows across the swale banks and becomes a more natural overland flow through existing coastal wetlands. Studying such a scenario on a design level involves the modeling of a coupled flow system of 1D canal network, 2D overland, and 3D subsurface.

Watershed Model WASH123D

The latest version of WASH123D [Yeh et al., 2003a] was used to study the spreader canal system. WASH123D is a physics-based [Yeh et al., 2003b], unstructured finite element model. The model is designed to simulate flow, chemical, and sediment transport in watershed systems. In modeling the flow of a coupled 1D channel, 2D overland, and 3D subsurface system, WASH123D integrates several components. They are (1) solving the 1D and the 2D diffusion wave flow models with the semi-Lagrangian approach, (2) solving 3D Richards equations with the Galerkin finite element method, and (3) accounting for interactions between different media (between 1D and 2D, 2D and 3D, and 1D and 3D) by imposing flux continuity and/or state variable continuity on the medium interfaces. The detail of these computations can be found in the WASH123D document [Yeh et al., 2003a]. Figure 1 depicts the coupling structure employed in WASH123D. Ideally, 1D channel network, 2D overland, and 3D subsurface flows are strongly coupled within each time step. However, this would introduce unaffordable computation because small time step sizes are usually required for resolving 1D channel routing. To make the computations affordable, in WASH123D each 3D time step may contain more than one 2D time step and each 2D time step more than one 1D time step. The fluxes through the surface-subsurface interface are computed based on the updated 3D subsurface computational result in each 3D coupling/nonlinear iteration, and the computed interface fluxes are taken as a fixed source/sink term in compute 1D and 2D flow during the same 3D coupling/nonlinear iteration. Likewise in each 2D coupling/ nonlinear iteration, the fluxes through the channel-overland interface are based on the 2D overland computational result, and the computed fluxes become a source/sink term in the 1D flow computation.

A Spreader Canal System

The top of Figure 2 depicts a conceptual model of a spreader canal system. As water is introduced from a delivery canal, the spreader canal is designed to distribute water to its

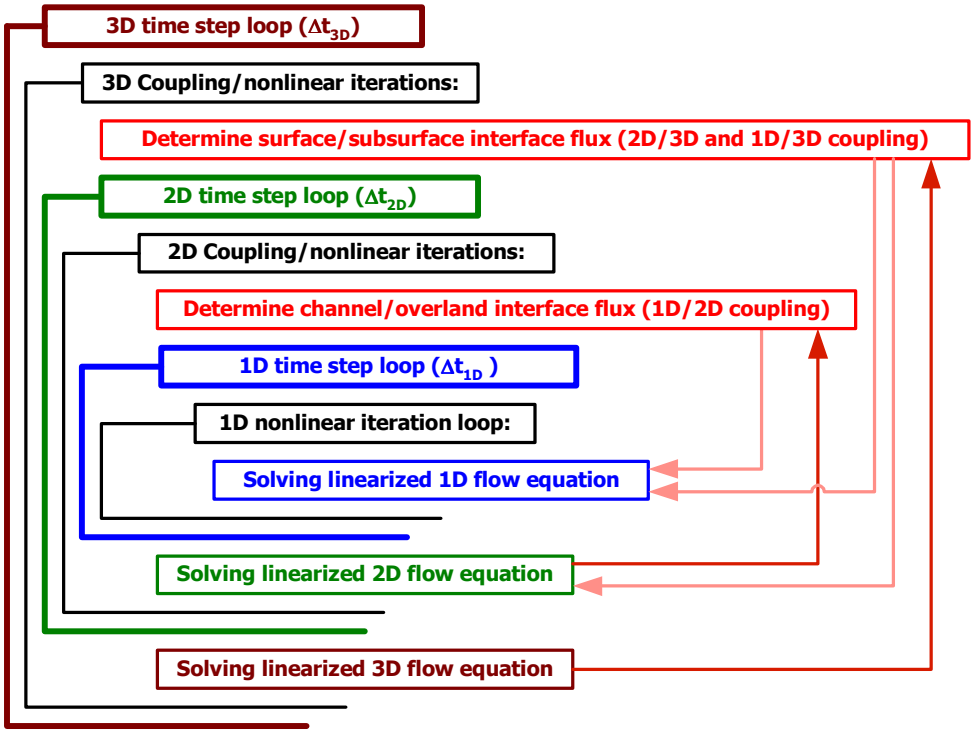

Figure 1. Coupling structure in WASH123D.

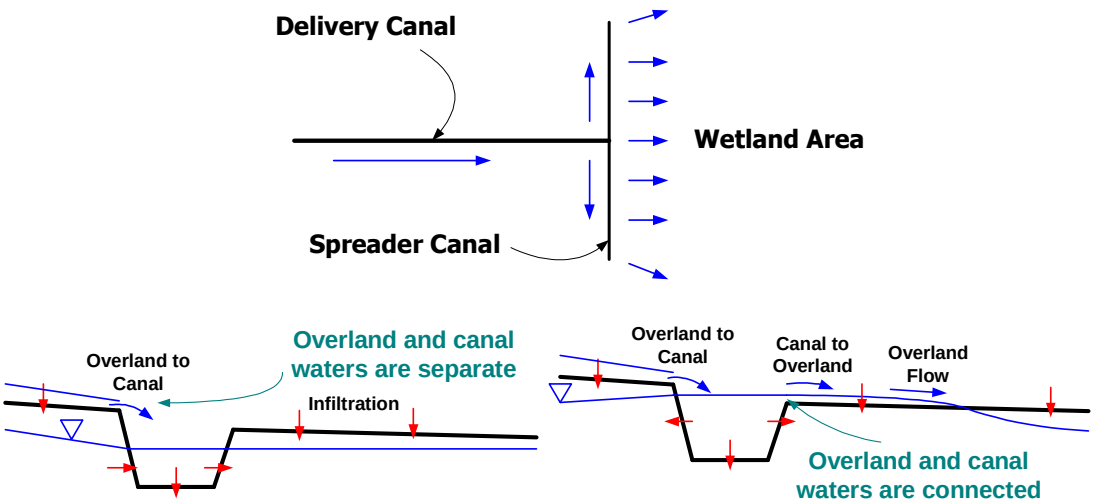

Figure 2. A conceptual model (top) and two scenarios (bottom) of the spreader canal

downstream wetland area in order to reduce the impact to the ecological system of the bay that is further downstream. The bottom of Figure 2 presents two scenarios that are associated with the spreader canal and need to be accounted for by the computational model: the left one shows a scene in which canal water is kept in canal, while the right one has canal water stage high enough to contribute to the downstream overland area. In

the left case, the canal collects water from its upland surface (overland and canal waters are separate here) but has no contribution to its downland surface area. In the right case, the canal receives water from its upland surface on one hand and gives out water to its downland surface (canal and overland waters are connected here) on the other hand. When the subsurface is also taken into account, surface-subsurface interactions through infiltration and seepage (red arrows in Figure 2) may play crucial roles in determining subsurface water table, overland water depth, and canal water stage. In WASH123D, flux continuity is ensured on the medium interfaces, while state variable continuity is imposed when waters between two media are connected.

A Demonstration Example

This hypothetical example demonstrates how WASH123D may help model and design a spreader canal system that includes 1D canal, 2D overland, and 3D subsurface flow. It used the topographic data in the BBCW project area (Figure 3) to construct the discretized domain of interest. The study area of this example is marked in Figure 3. A spreader canal was placed in the domain to distribute water that came in from the west boundary (marked with a red A in Figure 4). The 2D overland domain, which covered an area of approximately 1.1 square miles, was discretized with 28,340 elements and 14,390 nodes, where the mesh size was about 50 ft. The 1D canal embraced 91 elements, 94 nodes, one upstream boundary node (A in Figure 4), two dead ends (DE1 and DE2 in Figure 4), and one junction (J in Figure 4) to connect the three canal reaches. The underlying 3D domain contained 113,360 elements and 71,950 nodes. The width of the assumed rectangular canal was set 90 ft for Reach 1, 20 ft for Reach 2, and 60 ft for Reach 3 (Figure 4). The cross-sectional area was proportional to the depth, where the depth of the spreader canal was computed by solving 1D diffusive wave equations.

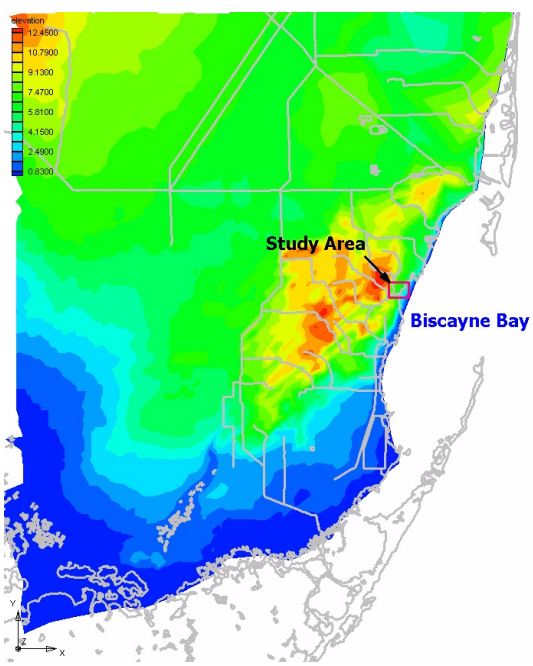

Figure 3. Location of the simulated area of the demonstration example

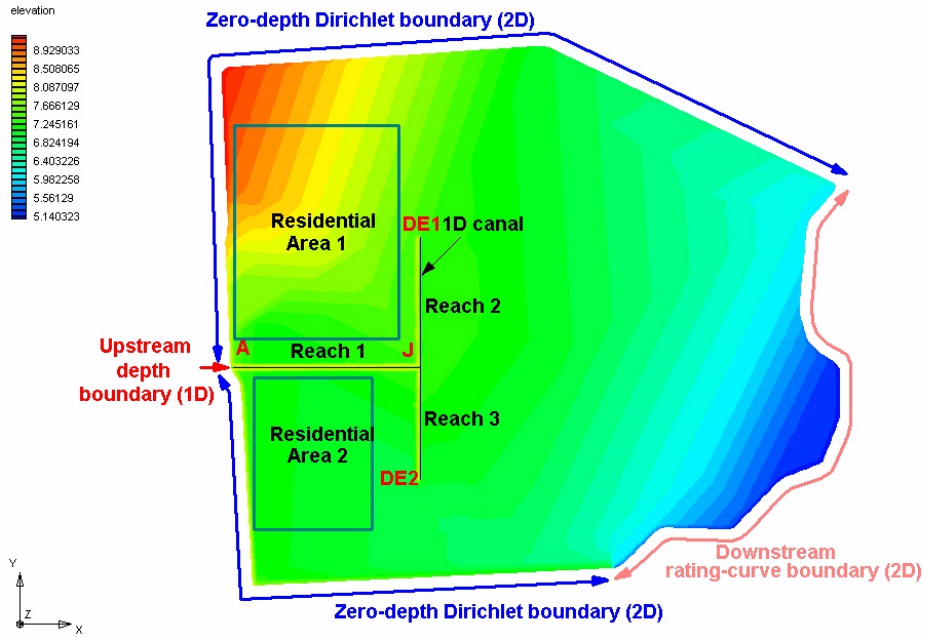

Figure 4. 1D canal and 2D overland boundary conditions used for the demonstration example

The Manning's roughness was set to 0.015 for 2D overland flow and 0.008 for 1D canal flow. The subsurface medium was sandy loam and was assumed isotropic, where the saturated hydraulic conductivity was 1,000 ft/day. The soil retention curves for the unsaturated zone were generated with the van Genuchten functions.

In computing 1D canal flow, a time-dependent water depth was given in Table 1 as the upstream boundary condition for the incoming water as indicated in Figure 4; a zero-velocity condition was applied at the two downstream dead-end nodes; and the continuity of both flow rate and water stage was enforced at the canal junction. In computing 2D overland flow, its north, west, and south boundaries were imposed the zero-depth boundary condition throughout the simulation; a depth-dependent flux (i.e., rating curve) was given on the downstream depth-dependent (rating curve) boundary (Figure 5); and a canal-overland interaction boundary condition was specified for the canal-related overland boundary sides, which includes (1) a depth-dependent flux when water flowed from overland to canal and overland water and canal water were separated and (2) a canal stage condition when flooding occurred (i.e., when overland water and canal water were connected). In computing 3D subsurface flow, an interface boundary condition that accounted for the interaction between surface and subsurface waters was applied to the top boundary face of the 3D domain; three total head boundary conditions were employed for (1) the subsurface boundary nodes associated with the 1D canal upstream boundary node on the west vertical boundary face (time-dependent head that matches 1D upstream boundary condition at the inlet (i.e., A in Figure 4), (2) all the subsurface nodes, except those mentioned in (1), on the west boundary (a constant head of 7.12 ft), and all the subsurface nodes on the east boundary face (a constant head of 4.95 ft) as shown in Figure 5; and an impermeable boundary condition for the rest of the vertical boundary

Table 1. Upstream water depth boundary condition used for the 1D canal flow

Time (seconds)	0	600	3600	7200
Depth (ft)	0.5	0.58	0.88	1.28

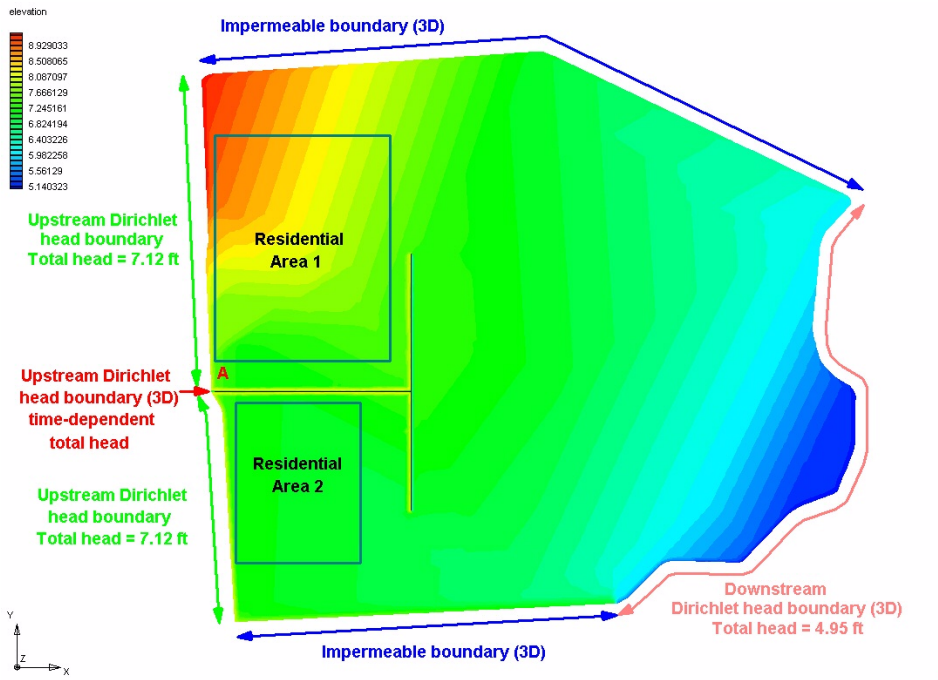

Figure 5. 3D subsurface boundary conditions used for the demonstration example

face and the bottom boundary. It is noted that for the vertical boundary face with total head specified, the Dirichlet boundary condition applied only to the boundary nodes below water table (i.e., in the saturated zone). For the vertical boundary face that was above water table, an impermeable boundary condition was assumed.

The initial pressure head in the subsurface was computed by solving the steady-state version of Richards' equation with a constant rainfall rate of 1.0×10^{-9} ft/s, while a constant water depth of 0.5 ft was enforced at the 3D boundary nodes that were corresponding to 1D spreader canal nodes and zero water depth was assumed at those corresponding to 2D overland nodes. For a demonstration purpose, such setup allowed us to expect water flow from the spreader canal to its neighboring overland regime within a short period of time after the transient simulation began. As the transient simulation began, the rainfall rate of 1.0×10^{-9} ft/s was applied throughout the entire simulation period of 2 hours. The time-step size was 60 seconds for computing 3D subsurface flow, 2 seconds for computing 2D overland flow, and 0.01 second for computed 1D canal flow. The absolute error tolerance was 1.0×10^{-5} ft for determining nonlinear convergence in computing 1D, 2D, and 3D flow.

Figure 6 shows the distribution of water depth on the 2D overland (left) and 3D subsurface pressure head on ground surface (right) at time = 2 hours. On the right half of the figure, the portion shaded with blue color has groundwater below ground surface, while the portion without shade has water table reach ground surface. It is seen that most water came out from Reach 3 of the spreader canal to overland due to natural terrain (the north ground was higher than the south ground). And because the ground south to the second dead end (i.e., DE2) was so flat, water coming out of spreader canal near DE2 could flow westward and affect the southeast corner of Residential Area 2. Moreover, as water stage increased with time in Reach 1 (not shown), which was subject to the increasing upstream water depth over time (Table 1), seepage through levee was observed around the upstream section of Reach 1 even though there was no water flow over the bank of Reach 1 throughout the simulation. This, as a result, would cause problems for people living in the north part of Residential Area 2 based on the topography around this area (Figure 7).

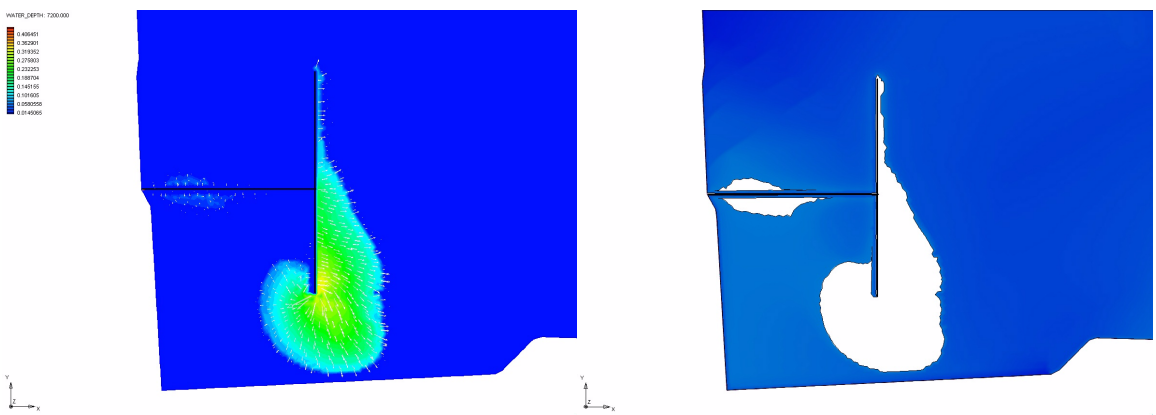

Figure 6. 2D overland (left) and 3D subsurface (right) flow results of Case 1 at time = 2 hr

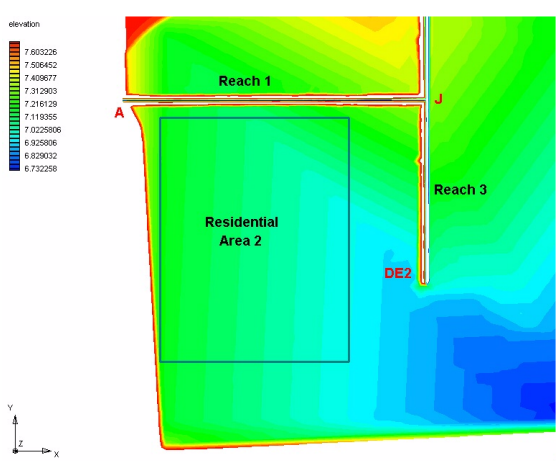

Figure 7. Topo of Residential Area 2 and its neighborhood before an extended levee was applied

To protect Residential Area 2 from getting flooded, a waterproof liner installed in Reach 1 and an additional levee from DE2 to the south overland boundary (Figure 8, left) were considered in this study. Table 2 lists the three cases included in this study: Case 1 serves as the base case where neither a liner nor an additionallevee is adopted; Case 2 has the liner; and Case 3 has both. The right of Figure 8 shows the topography around Residential Area 2 after an additional levee was applied. Figures 9 and 10 show the computational results of Cases 2 and 3, respectively, which are corresponding to Figure 6 for comparison. It is obvious from Figure 9 that the waterproof liner has prevented seepage from occurring. And from Figure 10, the extended levee has successfully stopped overland water from entering Residential Area 2.

Discussion

In studying a spreader canal system on the design level, such as the demonstration example above, a couple of important issues were revealed. First, a high-resolution mesh is needed to achieve desired goals on the design level. In the demonstration example, for instance, canal water was successfully directed to the downstream overland without impacting Residential Area 2 after a liner and an additional levee were installed. However, canal water was not evenly distributed to overland (Figure 10) as desired. To accurately determine what alternatives may help evenly distribute water, a high-resolution mesh that allows modelers to adequately catch most important physical

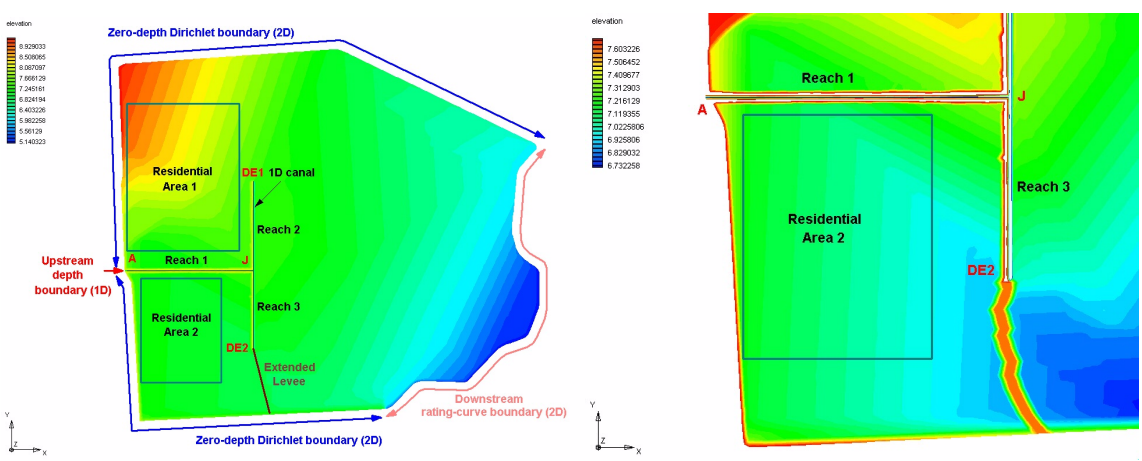

Figure 8. Using an extended levee to prevent flooding in Residential Area 2 (left) and the topography of Residential Area 2 and its neighborhood after an extended levee was applied (right)

Table 2. Three cases in the demonstration example

Case 1 (base case)	Case 2	Case 3
No liner in Reach 1 No extended levee	Liner in Reach 1 No extended levee	Liner in Reach 1 Extended levee applied

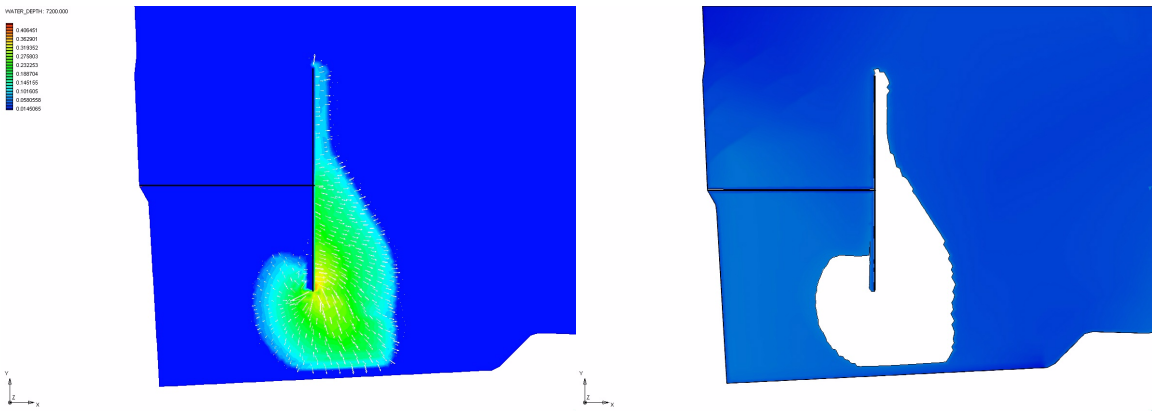

Figure 9. 2D overland (left) and 3D subsurface (right) flow results of Case 2 at time = 2 hr

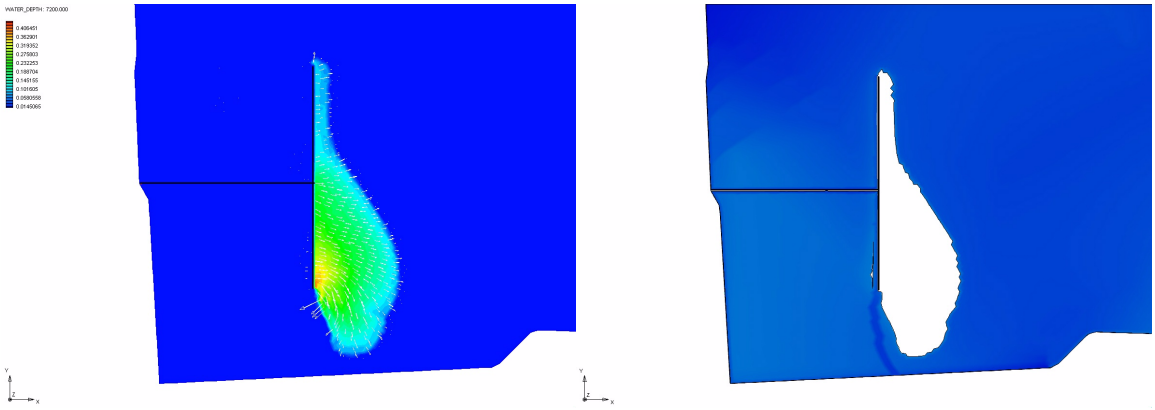

Figure 10. 2D overland (left) and 3D subsurface (right) flow results of Case 3 at time = 2 hr

processes and necessary details is a MUST. But it may also demand a lot of computer resources for a complete study. Moreover, high-resolution mesh usually requires small time intervals to reach convergent solutions when the system contains nonlinearity. This will further multiply the demand of computer resources. To save computational time in practice, one solution may be the use of the inset-model approach to first obtain solutions from regional models where mesh resolution is much lower, and use the regional model solution to set up boundary conditions for the desired design-level model.

Secondly, the time interval of 3D flow is crucial in accounting for the surface-subsurface interaction. Large 3D time intervals seem to help reduce computational effort because one large 3D time step may include many 2D time steps and even more 1D time steps. However, it has been determined through numerical experiments (not shown here) that strong coupling between surface and subsurface flow modules usually requires very small 3D time steps to reach convergent solutions, especially during the transition period when ground surface is from dry to wet, or vise versa. The adoption of weak coupling can relieve this convergence concern to a certain extent, but if the 3D time interval is too

large, it will produce inaccurate results even convergent solution can be obtained. One solution to this problem maybe the use 3D time intervals small enough to resolve important physical phenomena plus the weak coupling scheme (i.e., compute the interface flux based on the results at the previous 3D time) to account for surface-subsurface interactions. Sensitivity analysis on the 3D time interval will be essential to determine adequate values.

Summary

This paper, through a demonstration example, shows the capability of the WASH123D model in helping design a spreader canal system. While intensive computation is essential in studying a system on the design level with a first-principle, physics-based model, the inset-model approach and the adoption of weak coupling to account for surface-subsurface interactions may help reduce computational time. Efforts to address the issues aforementioned in the Discussion section are needed.

Acknowledgments

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