Using the Parallel WASH123D Code to Simulate Overland-Subsurface Interactions

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Abstract

WASH123D model is a first-principle, physics-based model, where water flow and/or contaminant and sediment transport within a watershed system are computed. In the WASH123D model, a watershed is conceptualized as a coupled system of 1-D canal /stream network, 2-D overland regime, and 3-D subsurface media. It is designed to answer the environmental issues concerning both water quantity and quality. To reach numerical solutions with reasonable and tolerable computer time for a regional scale watershed simulation, numerical algorithm improvement and code parallelization are two essential tasks when a distributed numerical model, WASH123D, is used. This paper presents the code parallelization approach, followed by demonstrating its scalability performance. The test problem of a large mesh uses the topographic data in the C-111 Spreader Canal Project.

Background

The C-111 Spreader Canal Project is one component of the more than 60 restoration plans under the Comprehensive Environmental Restoration Plan (CERP) and has a goal to provide water deliveries that will enhance the connection between the natural areas in the Southern Glades and Model Lands area of South Dade County. The spreader canal will be designed and built to connect these natural areas hydrologically by establishing sheet flow of water that will sustain healthy ecosystems. The project will also provide more natural sheet flow to Florida Bay by eliminating point sources of freshwater discharge through C-111 canal to the Manatee Bay and Barnes Sound.

Design the spreader canal is not an easy task due to the complex hydrologic process in these areas (flat terrain, surface water and ground water interactions). There is a need of physics-based model to simulate interaction between surface water and groundwater.

WASH123D [Yeh, et al., 2003] has the capability to simulate these complex hydrologic systems and is selected to model the C-111 spreader canal system.

Code parallelization approach

The parallelization of the WASH123D program intends developing software tools, which would assist in code migration from serial to parallel platform. In order to compliant with the object-oriented programming concept, the software design is then focused on the data structure design, parallel software tool development, and parallel tool integrations.

The data structure of the parallel WASH123D is redesigned using the C language, while the computational kernel is kept as what it was because there is no parallelization involved and FORTRAN is still a preference in computational performance. Three `WashMesh` objects, which describe 1-D river/stream network, 2-D overland regime, and 3-D subsurface media, and one `WashCouple` object are constructed to discretize the entire computational domain. Each `WashMesh` object may include `vtxDomain` and `elementDomain`, which are created and managed by the DBuilder—a parallel data manager encapsulating all the MPI function calls and domain partitioning—developed for the DoD HPC users community. The `WashCouple` may include the `coupler` for (1-D, 2-D), (1-D, 3-D), and/or (2-D, 3-D). In the `coupler`, the message passing implementation between different dimensions of meshes is embedded. Moreover, the `coupler` object is built to avoid the dependency between meshes when partitioning. Figure 1 depicts the concept of the `coupler` implementation. In the figure, all of four processors participate in 2-D and 3-D simulations. Because no dependency is specified between them when partitioning, there is no guarantee that the top of the subdomain that the processor owns in 3-D is exactly the subdomain owned by the processor in 2-D. As shown in the figure, processor P3 owns the 2-D subdomain, which is the top of the 3-D subdomains owned by processor P2 and P3. Likewise, the top of the 3-D subdomain that processor P1 owns is a partial subdomains partitioned to P0 and P1 in 2-D. Therefore, the message passing from 2-D to 3-D and from 3-D to 2-D is then setup in the `coupler` as shown in the red and blue dashed arrow lines, respectively.

When the Picard method is adopted to solve the nonlinearity of the 2-D overland flow, the linearized equation with the diffusion wave approach implemented, can be solved by particle tracking methods to compute the total-time derivative term and by manipulating integration along the tracking path for the source/sink terms. The parallel PT (particle tracking) software facilitated with an ODE solver for unsteady flows is integrated with the parallel WASH123D. Since a well design Application Programming Interface (API) is provided, the integration work is much leveraged. Details of PT development and PT integration can be found elsewhere [Cheng et al., 2004a; 2004b].

Experimental results

Topographic data at the C-111 Spreader Canal Project areas are used to demonstrate how the parallel computation code is more efficient that a single-processor system in the regional scale watershed system. Figure 2 shows the location of the application site. Figure 3 shows the colored contour of land surface elevation. The 2-D overland domain, which covers about 500 square miles, is discretized with 8,077 nodes and 15,895 elements. The underlying 3-D domain contains 56,539 nodes and 95,370 elements.

The Manning's roughness was set to 0.02 for the overland areas. The subsurface medium consists of two materials, Miami Oolite and Fort Thompson. The saturated hydraulic conductivity was set to 1000 ft/day for Miami Oolite and 2000 ft/day for Fort Thompson. The soil retention curves for the unsaturated zone were generated with the van Genuchten functions.

In computing 2-D overland flow, on the upstream boundary a time-dependent stage was specified, and a depth-dependent flux (rating curve) was given on the downstream boundary. Figure 4 shows the boundary conditions for 2-D overland flow. As the transient simulation started, a constant recharge rate of $1.0\text{x}10^{-6}$ ft/hr was applied for 15 day simulation. It took about 3 hours to complete a 15-day simulation on Compaq AlphaServer UNIX workstation (ES40) for 2-D overland flow.

For 3-D subsurface flow simulation, an impermeable boundary condition was assumed for the bottom boundary face; a time-dependent head was specified at the upstream boundary and at the downstream boundary. Figure 5 shows the boundary conditions for 3-D subsurface flow. As the transient simulation started, a constant recharge rate of $1.0\text{x}10^{-6}$ ft/hr was applied for 15 day simulation. It took about 2 hours to complete a 15-day simulation on the same UNIX workstation for 3-D subsurface flow.

Figure 6 shows the simulated water depth at the time = 72 hours. Figure 7 shows the simulated subsurface pressure head at the end of the 15 day.

Table 1, 2, and 3 lists the wall clock time vs. number of processors for 2-D overland flow simulation and 3-D subsurface flow simulation.

Figure 8 plots the wall clock time on the Compaq SC45 machine vs. number of processors for 2-D overland flow simulation and 3-D subsurface flow with the linear solver BlockSolve95 [Jones and Plassmann, 1995] and ERDC2. The Compaq SC45 machines at ERDC MSRC are configured with 128 nodes connected by a 64-port, singl-rail Quadrics high-speed interconnect switch. Each node contains four 1 GHz Alpha EV 68 processors and four GB of RAM. From this figure, one can observe that the parallel efficiency is above 50 percent when there are less than 8 processors requested for the simulation. The problem size is not big enough is the major reason why the parallel performance is getting worse when more processors are involved. To demonstrate the parallel performance, an example with significant computational load compared with communication load is required. In addition, one can also notice that the BlockSolve95 is more efficient than the ERDC2 linear system solver.

Summary

Based on experimental demonstration for one year simulation, it would take about 72 hours for 2-D overland flow and 48 hours for 3-D subsurface flow on a single-processor UNIX workstation. For parallel computation, it would take 9.9 hours to complete one year simulation of 2-D overland flow and 4.46 hours for 3-D subsurface flow on a 16-processor Compaq SC45 machine. The WASH123D team is continuing forward the development of the coupling module.

References

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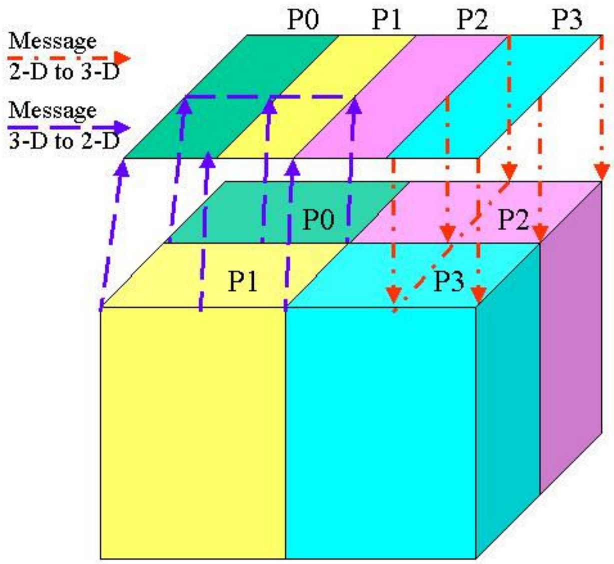

Figure 1. The concept of the coupler implementation

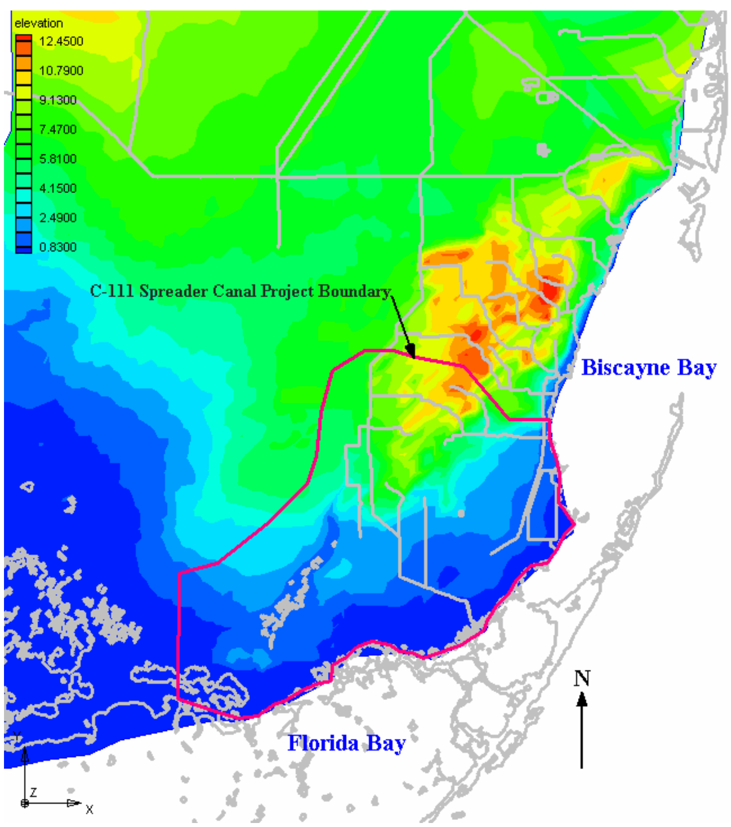

Figure 2. Location of C-111 Spreader Canal Project

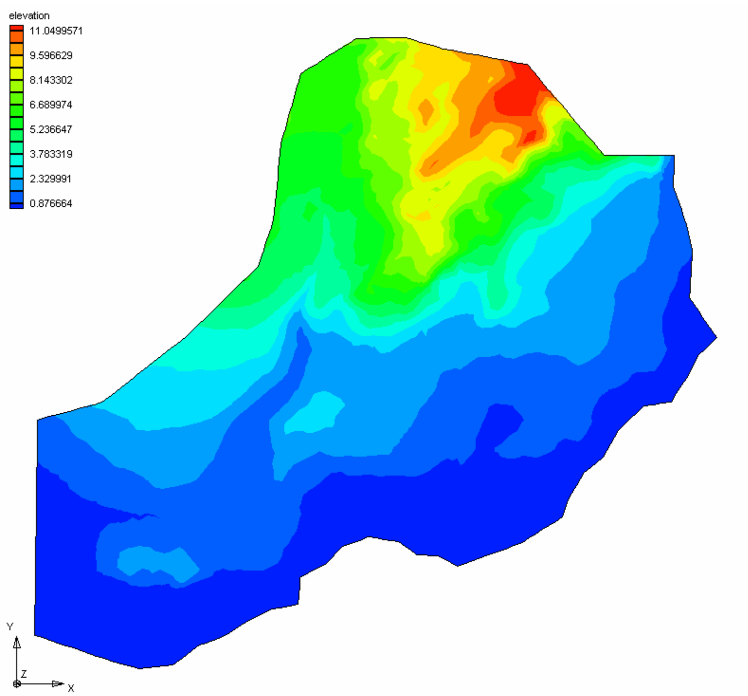

Figure 3. Color shaded contours of land surface elevation of 2-D overland domain

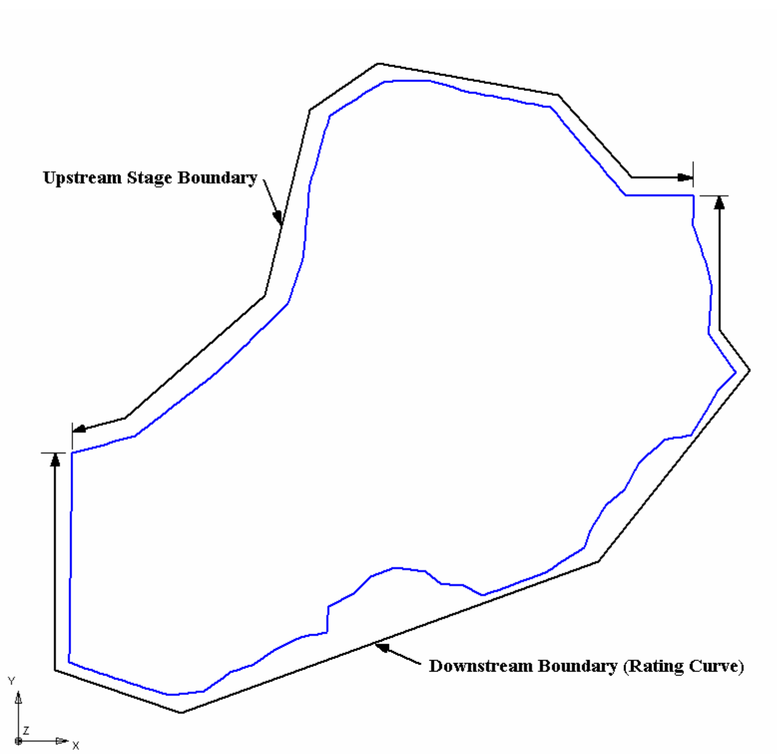

Figure 4. Boundary condition of 2-D overland flow

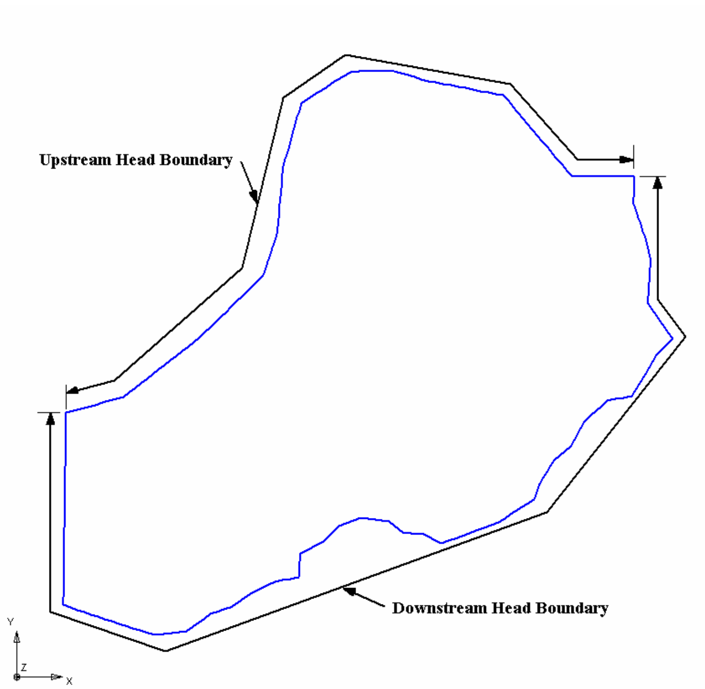

Figure 5. Boundary condition of 3-D subsurface flow

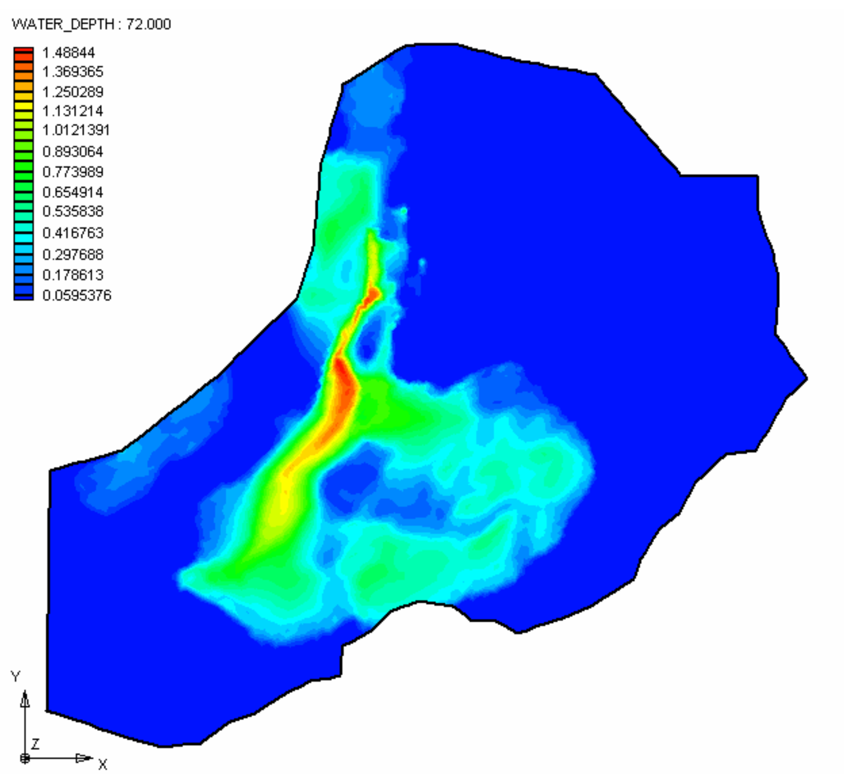

Figure 6. Simulated overland water depth at time = 3day

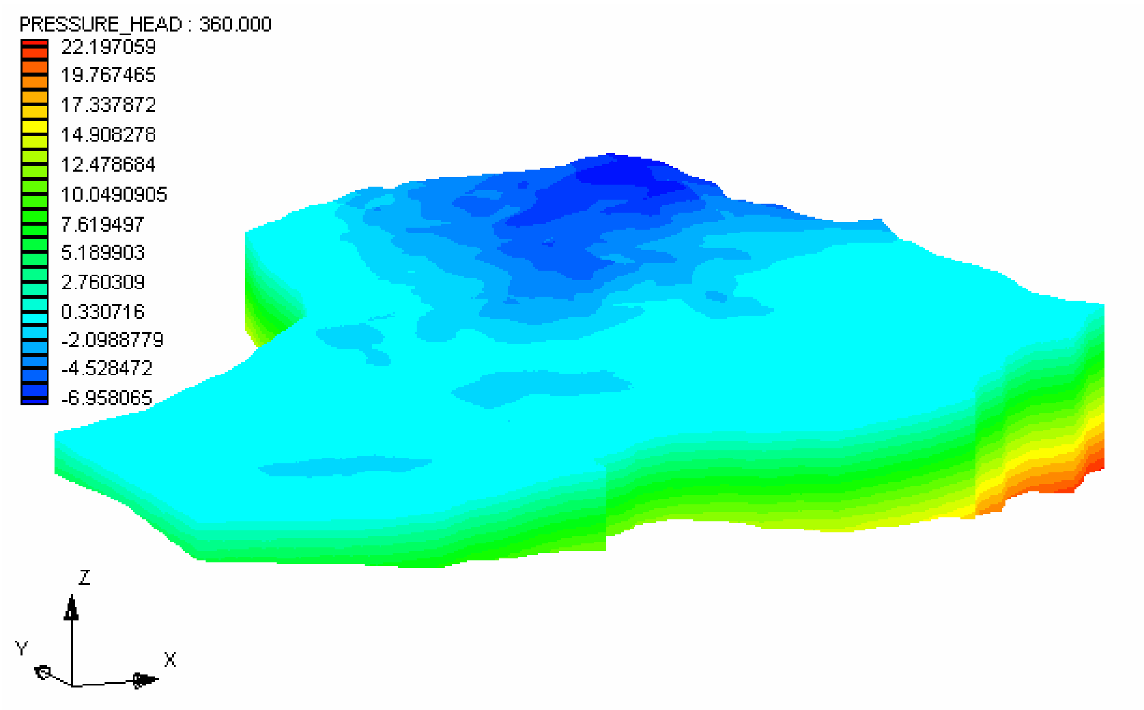

Figure 7. Simulated subsurface pressure head at time = 15day

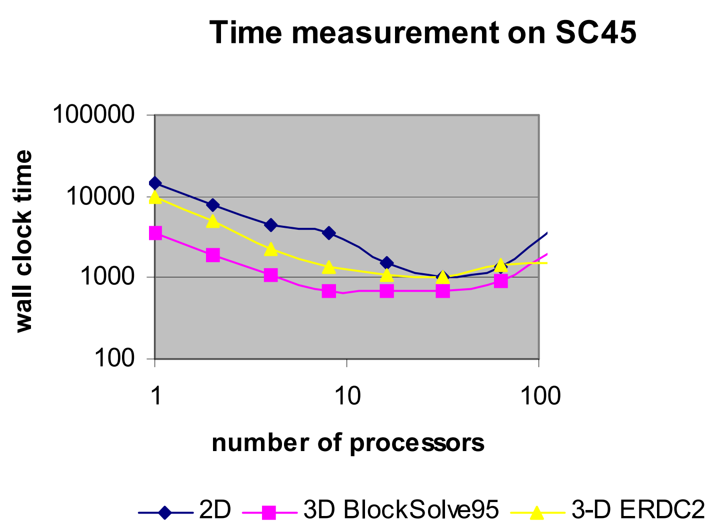

Figure 8. Wall clock time on Compaq SC45 machines

Table 1. Scalability on the Compaq SC45: timings for 2-D overland flow simulation

Number of processor	Time (sec)	Speedup over 1 processor	Parallel efficiency
1	14688.38	-	-
2	7751.38	1.895	0.947
4	4389.8	3.346	0.837
8	3586.98	4.095	0.512
16	1478.71	9.933	0.621

Table 2. Scalability on the Compaq SC45: timings for 3-D subsurface flow simulation (ERDC2 linear solver)

Number of processor	Time (sec)	Speedup over 1 processor	Parallel efficiency
1	9673.39	-	-
2	4899.49	1.974	0.987
4	2297.75	4.210	1.052
8	1387.26	6.973	0.872
16	1070.73	9.264	0.565

Table 3. Scalability on the Compaq SC45: timings for 3-D subsurface flow simulation (BlockSolve95 solver)

Number of processor	Time (sec)	Speedup over 1 processor	Parallel efficiency
1	3610.54	-	-
2	1865.47	1.935	0.968
4	1053.69	3.427	0.857
8	698.74	5.167	0646
16	668.39	5.402	0.338