# THE USACE TOOLBOX OF MODELS FOR MULTI-DIMENSIONAL SURFACE WATER-GROUNDWATER INTERACTION STUDIES

**Cary Talbot, Research Hydraulic Engineer, US Army Corps of Engineers, Vicksburg, MS, Cary.A.Talbot@erdc.usace.army.mil**

**Abstract** The System-Wide Water Resources Program (SWWRP) was begun by the US Army Corps of Engineers (USACE) in October 2004 as a 7-year research program to develop and field tools for integrating the essential components of water resources management across watershed systems. An important component of the Watershed Hydrology Simulation project in SWWRP is the development of a suite of tools for performing multi-dimensional surface water-groundwater (SW-GW) interaction studies. This toolbox of numerical models includes codes of varying complexity and fidelity, providing the USACE with a range of tools that can be selected based on the study needs. Low-fidelity simulators are needed for studies where computational speed is of greater importance while high-fidelity simulators are needed for studies where the highest degrees of accuracy are required. A current limitation of SW-GW interaction models is that simulation run times can be lengthy, particularly for high-fidelity studies. Research is underway in SWWRP to achieve significantly faster model run times for SW-GW applications by use of models designed for high performance computing (HPC) platforms, mesh adaption and other techniques. This paper will discuss the simulators included in the toolbox and their design enhancements aimed to achieve faster run times for SW-GW interaction applications.

## INTRODUCTION

Federal water supply, water quality, and environmental remediation studies increasingly demand that interactions between surface and subsurface hydrologic systems be considered and simulated in order to provide decision-makers with accurate and defensible alternatives. The US Army Corps of Engineers (USACE) and other federal and state agencies are currently engaged in the application of coupled surface water-groundwater (SW-GW) interaction simulation models in large-scale wetland restoration projects in South Florida, coastal Louisiana and other areas. In some cases, simulations of many hundreds of square miles over multiple decades are required to evaluate long-term restoration alternatives. Other projects are of a smaller scale yet due to the integrated nature of the surface and subsurface hydrologic systems, they require the application of SW-GW interaction simulators for successful completion.

Coupling SW-GW hydrologic processes in a single simulator presents unique physical and numerical challenges. One challenge lies in the fact that the surface and subsurface domains behave very differently from a hydrological perspective. Surface water flow is generally approximated with some form of either the de St. Venant (2D shallow water) or Navier-Stokes (3D) equations, which are complex non-linear partial differential equations. By contrast, with the exception of the unsaturated (vadose) zone, subsurface flow is approximated using some form of Darcy’s Law, a linear relationship. Parameterization of the surface water flow equations can be reliably accomplished by sampling the bathymetry and flow velocity and depth while parameterization of the subsurface domain remains a difficult challenge. Another challenge in coupling SW-GW computations arises from the disparity in temporal scales involved in simulating each domain. Numerical stability and accuracy requirements often dictate that surface water computations use time steps on the order of minutes and possibly even seconds while it is rare that groundwater computation require anything smaller than day-long time steps. Lastly, except in cases where the surface water and groundwater are in direct contact, the domains are separated by the vadose zone where both water and air fill the voids between the solid particles that comprise the soil matrix. Vadose zone flow, as with saturated groundwater flow, is dependant on the hydraulic conductivity, a measure of the speed that water can move through the soil matrix. While constant for a saturated soil, this parameter varies in a highly non-linear fashion as the moisture content of the soil changes. Unsaturated hydraulic conductivity commonly varies over anywhere from four to ten or more orders of magnitude in the range of moisture content normally encountered in field conditions, depending on soil type (Rawls et al., 1982).

Taken together, all of these challenges present a formidable problem to successful simulation of integrated SW-GW systems. However, the need to perform fully coupled SW-GW interaction studies exists and various tools are under development within the USACE to meet this need. The System-Wide Water Resources Program (SWWRP) was begun in October 2004 as a 7-year research program to develop and field tools for integrating the essential components of water resources management across watershed systems. An important component of the Watershed Hydrology Simulation project in SWWRP is the development of a suite of tools for performing coupled, multi-dimensional SW-GW interaction studies. This toolbox of numerical models includes codes of varying complexity and fidelity, providing the USACE with a range of tools that can be selected based on the study needs. This paper will discuss the capabilities and development of these tools and present some recent applications.

## TOOLBOX OF SW-GW INTERACTION SIMULATORS

Simulators for interactions between surface and subsurface hydrologic systems should be chosen based on the importance of each physical process within the context of the study needs and the capabilities of the available models. Accordingly, the toolbox of SW-GW interaction simulators includes models that provide a range of capabilities for multi-dimensional SW-GW interaction modeling. A low-fidelity simulator is needed for studies where computational speed is of greater importance while studies where the highest degrees of accuracy are needed require a high-fidelity simulator. Currently there are three models being developed that belong to the multi-dimensional coupled SW-GW interaction modeling toolbox. They are GSSHA, WASH123D and ADH.

**GSSHA** The need to simulate surface water flows in watersheds with diverse runoff production mechanisms has prompted the US Army Engineer Research & Development Center (ERDC) to develop a physically based hydrologic model called Gridded Surface/Subsurface Hydrologic Analysis (GSSHA). GSSHA is a reformulation and enhancement of the two-dimensional, physically based finite difference model CASC2D. GSSHA simulates stream flow generated by both infiltration-excess and saturation-excess mechanisms, as well as exfiltration, and groundwater discharge to streams. The model employs mass-conserving solutions of partial differential equations and closely links the hydrologic components to assure an overall mass balance (Downer and Ogden 2004). GSSHA is developed in a partnership between Fred Ogden of the University of Wyoming and a team of researchers at ERDC.

GSSHA is a process-based model that approximates many different hydrologic processes by the various methods listed in Table 1.

**Table 1.** GSSHA physical processes and approximation methods.

| Process | Approximation Method(s) |
|---|---|
| Precipitation distribution | Theissen, inverse distance square weighted |
| Snowfall accumulation and melting | Energy balance |
| Precipitation interception | Two parameter |
| Overland water retention | Specified depth |
| 1D Infiltration | G&A, multilayered G&A, GAR, RE |
| Overland flow routing | 2D diffusive wave: Explicit, ADE, and ADEPC |
| Channel routing | 1D up-gradient explicit diffusive wave |
| Evapotranspiration | Deardorff, Penman-Montheith with seasonal canopy resistance |
| Soil moisture in vadose zone | Bucket, RE |
| 2D Lateral groundwater flow | 2D vertically averaged |
| Stream/groundwater interaction | Darcy's law |
| Exfiltration | Darcy's law |

Note: Approximation methods in the GSSHA model: G&A=Green and Ampt (1911); GAR=Green and Ampt with Redistribution (Ogden and Saghafian 1997); RE=Richards' equation (1931); ADE=alternating direction explicit; ADEPC=alternating direction explicit with prediction correction. After Downer and Ogden (2004).

Recently SWWRP has funded the development of sediment transport (Ogden et al. 2005a), wetlands hydrology (Byrd et al. 2005), and storm drainage network simulation (Ogden et al. 2005b) capabilities in GSSHA, which are now being fielded. In particular, the wetlands hydrology model additions greatly extend the capabilities of GSSHA to simulate the complex flow conditions that typically occur in wetlands where both groundwater and surface runoff conditions exist. The exact mechanism that is dominant at any particular time is most accurately defined as a function of the vegetative height and flow depth. Thus, GSSHA computes flow in the wetland differently based on one of three possible conditions. When the water depth is below the wetland retention depth, flow is computed as Darcian seepage. When the water depth exceeds the average vegetative height, flow is comprised of both seepage flux and Manning's equation flux that conceptually considers the bent-over condition of the vegetation. Finally, when the water depth is greater than the retention depth but less than the vegetative height, flow is computed from a weighted average of the seepage and Manning's flux that accounts for the vertical vegetation condition (Figure 1).

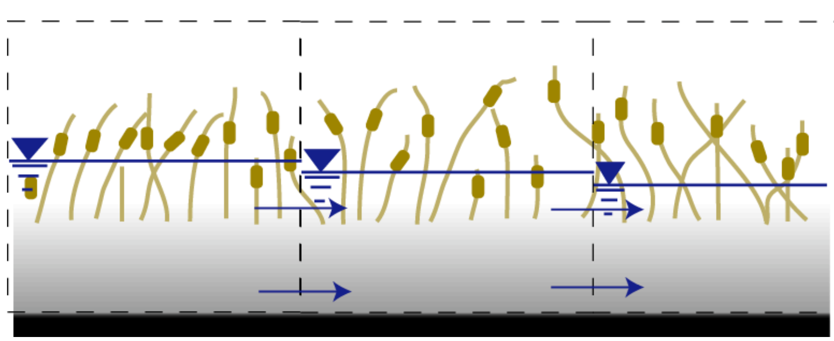

**Figure 1.** Wetland flow comprised of both overland and seepage components. Byrd et al. (2005)

The wetlands hydrology model in GSSHA has successfully been applied in two recent studies. In the first, four placements of a proposed wetland were evaluated to determine the impacts on flow characteristics for various design storms were considered on the Coon Creek watershed in northern Illinois. In the second study, proposed wetland creation on a portion of the Rio Grande in urban Albuquerque, New Mexico was simulated to determine the impacts of the wetland on local groundwater elevations during various design storms. The ability of GSSHA to model the interaction between surface water and groundwater flow domains was key to the success of these projects in simulating the hydrologic system response to the design conditions.

**WASH123D** WASH123D is a first principle, physics based watershed model. For the purposes of the model's capabilities, a watershed includes an overland regime including management structures such as storage ponds, pumping stations, culverts, and levees; a river/stream/canal network including natural junctions and control structures such as weirs, gates, culverts, and pumping; and subsurface media including management devices such as pumping and injecting wells, drainage pipes, and drainage channels. The model is composed of hydrologic and hydraulic flow, thermal and salinity transport, and reactive water quality transport. Three options are included in modeling flow on the land surface and in river/stream/canal networks: kinematic wave, diffusion wave, and dynamic wave approaches. Flow through subsurface media is described by the Richards equation where vadose and saturated zones are considered a unified media system (Yeh et al. 2005). Finite element meshes of one, two and three dimensions are used to discretize the river/canal/stream, overland and subsurface flow domains, respectively. WASH123D has been developed in a partnership between George Yeh of the University of Central Florida and a team of researchers at ERDC.

One of the critical issues in an integrated, multi-dimensional SW-GW interaction model is its treatment of coupling between the flow domains. Owing to the complexities of coupling SW-GW systems, some approaches formulate a linkage term between the river/stream/canal dynamics and subsurface fluid flow (e.g., MODNET (Walton et al. 1999)) or between overland and subsurface flows (e.g., MIKE SHE (Refsgaard and Storm 1995)). The linkage term usually introduces non-physics based parameters. As a result, such watershed models take on parametric characteristics even though a first principle, physics based approach was used for each domain. A rigorous treatment of coupling domains should be based on the continuity of mass, momentum, and state variables across domain interfaces. This is the approach taken with WASH123D and described in Yeh et al. (2005).

The rigorous treatment of the coupling of domains together with the extensive array of 1-D and 2-D management structures provided WASH123D with the necessary advantages to be selected as the model for two large-scale projects in South Florida. The Biscayne Bay Coastal Wetlands (BBCW) study, one of the first projects being conducted as part of the Comprehensive Everglades Restoration Plan (CERP), concentrates on evaluating various alternatives for changes to pump stations, spreader swales, stormwater treatment areas, levees, culverts and canals over a 13,600 acre area. The project purpose is to rehydrate wetlands and reduce point source discharges of fresh water to Biscayne Bay. The WASH123D model for this study was completed in two stages. First a coupled 2-D/3-D model was calibrated to establish the overland and subsurface parameters (Figure 2). The 1-D canal network was then added to a subset of the larger 2-D/3-D model and the coupled 1-D/2-D/3-D model was calibrated and validated against data sets from wet, dry and average years (Figure 3).

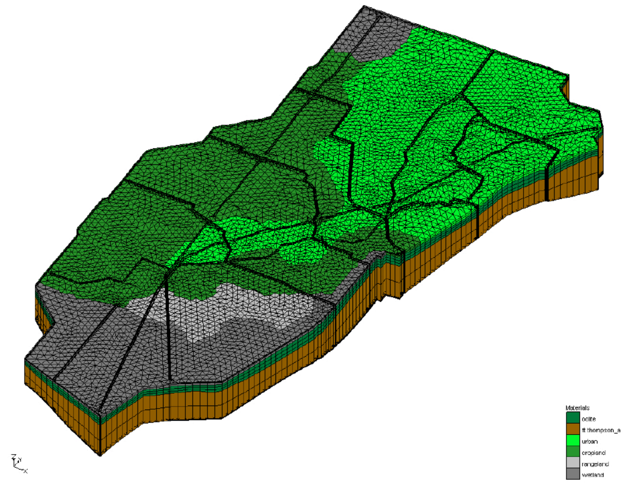


**Figure 2.** WASH123D 2-D/3-D mesh for BBCW study. The dark lines represent the fine mesh density along levees and canals.

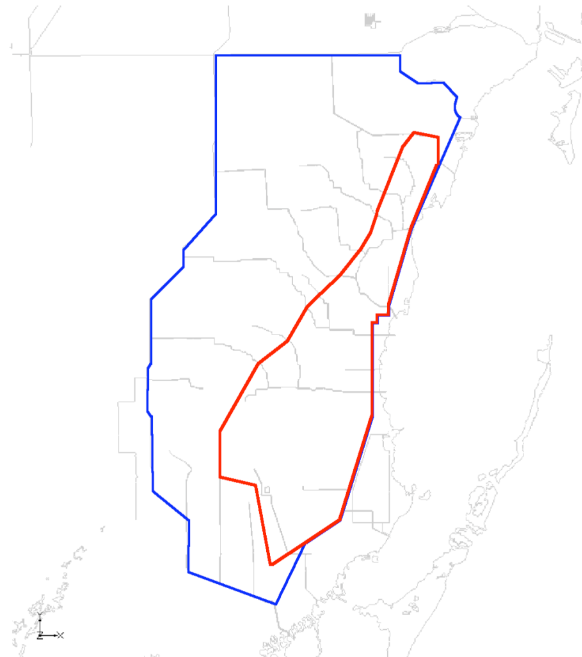

**Figure 3.** Comparison of 2-D/3-D (blue) and 1-D/2-D/3-D (red) mesh boundaries for BBCW study.

In assessing the combined impacts of the dozens of current and planned CERP projects, the need was realized for a flexible and powerful engineering model capable of detailed hydrologic and hydraulic processes using a physics based, first principles approach at a range of scales. WASH123D has been selected as the numerical model for the Regional Engineering Model for Ecosystem Restoration (REMER) project for the entire CERP project area (Figure 4). The model boundaries cover an area that is approximately 40% of the State of Florida. Development of the model for this area is underway and consists of a massive effort in collection, assimilation and consolidation of data.

Given the scale of this study, unique approaches have been required for every phase of model construction, execution, calibration and validation. Due to the size of the computational mesh for a model of this scale, even high-end computing platforms are insufficient to meet the demands of running this model. A team of High Performance Computing (HPC) experts has created a parallel version of WASH123D that will allow the REMER model to be run on HPC resources available in the Major Shared Resource Centers (MSRC) of the US Department of Defense (DoD). By utilizing the combined computing power of hundreds of processors at once, the REMER WASH123D model will provide the ability to evaluate engineering alternatives for CERP projects in a system-wide fashion. WASH123D in either serial or parallel form provides a powerful tool to the USACE for evaluation of both small and large scale systems in a detailed, first principle, physics based fashion.

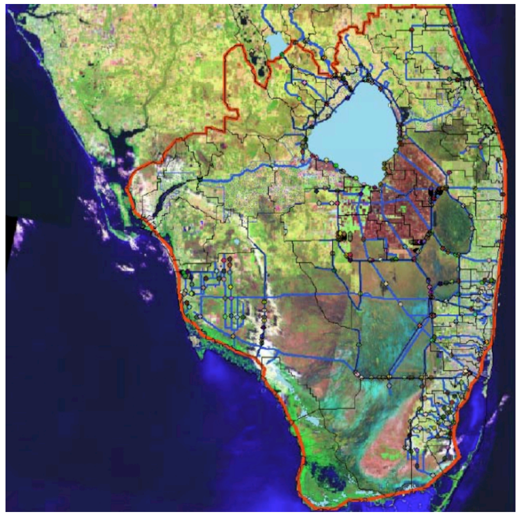

**Figure 4.** Approximate location of REMER model boundary (red) in South Florida.

**ADH** Numerical modeling principles dictate that the distance between computational nodes must need be relatively small where gradients in the parameters of interest are large. In the case of a coupled SW-GW interaction model that simulates a natural hydrologic condition over time, the location of high gradients can vary dramatically as various natural events (rainfall, runoff, flooding, etc.) occur. Using conventional models, this would require that fine mesh resolution be placed throughout the mesh where high gradients are possible, even if only for a small portion of the model run. Adaptive grid models, however, sense when gradients in a given location have increased and locally refine the mesh to an appropriate level. If local gradients again decrease, the process is reversed and the mesh is coarsened. In this fashion, adaptive models provide an efficient use of computational resources for large scale and/or highly detailed models. The Adaptive Hydraulics/Hydrology (ADH) model under development at ERDC provides spatial and temporal adaption as a key feature for coupled SW-GW interaction studies (Schmidt 1997).

ADH is similar to WASH123D in that it is a first principle, physics based finite element model with rigorous coupling between surface and subsurface domains. However, ADH differs from WASH123D in that it was conceived with a modular design, allowing for new modules to be easily added to the code. At present ADH provides modules for 2-D shallow water, 3-D Navier-Stokes fluid flow and 3-D variably saturated groundwater flow computations. SWWRP is currently funding the development of non-cohesive and cohesive sediment erosion/deposition and transport, turbulence effects and multi-constituent transport modules that are currently being added to ADH.

Part of the design criteria for ADH has been aimed at improving the numerical speed of complex computations whether it is for non-hydrostatic 3-D fluid flow in supercritical channels or unsaturated groundwater seepage. ADH has been designed from the beginning as both a serial and parallel code allowing execution on desktop or HPC computational platforms as dictated by the complexity and scale of the problem. Finally, sophisticated pre-conditioners and solvers have also been designed for ADH to reduce the run times in addition to the adaptive capabilities previously discussed.

ADH has been applied in several SW-GW interaction studies as a demonstration of its capabilities. Shown in Figure 5 are the groundwater pressure head contours displayed on the 3-D mesh from a SW-GW interaction model for Pool 8 on the Upper Mississippi River. In this simulation it is possible to observe the response of the groundwater pressures to extraction of water by the river and changing boundary conditions.

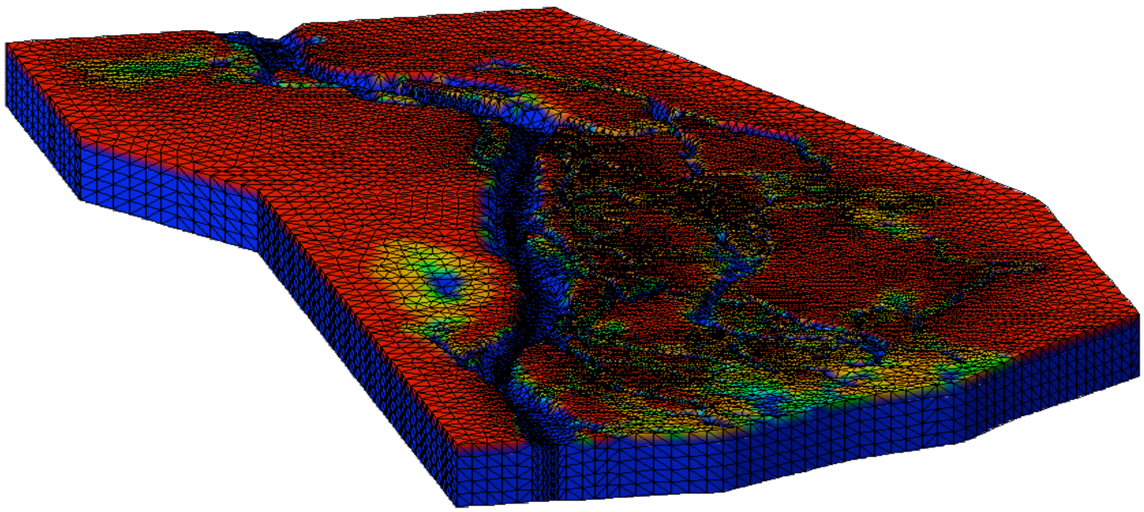

**Figure 5.** Pool 8 groundwater pressure head contours on ADH mesh.

## CONCLUSIONS

SWWRP is funding the development of a toolbox of multi-dimensional, coupled SW-GW interaction simulators. At present, the toolbox includes three models of varying complexity and capability. GSSHA, by virtue of its finite difference formulation and 1-D unsaturated/2-D saturated groundwater flow computations represents the lower-fidelity but faster running model for simulations where computational speed is of import and the groundwater flow regime can be adequately simulated with a 2-D flow model. WASH123D provides detailed and complete simulation capabilities for high-fidelity simulations, particularly in systems that include highly managed surface water systems such as detention basins, canals, flow control structures, pump stations and levees. ADH provides rigorous coupled SW-GW interaction computations along with adaptive mesh refinement and sophisticated numerical enhancements to achieve faster run times in high-fidelity simulations. Both WASH123D and ADH provide the option of running on serial as well as parallel computational platforms. Parallelization of GSSHA will be performed as a future SWWRP research effort.

As with all SWWRP-developed technologies, all of these tools are supported within the USACE-sponsored XMS family of modeling systems. At present GSSHA is supported in the Watershed Modeling System (WMS) while WASH123D and ADH are supported in the Groundwater Modeling System (GMS). The future will see the interfaces to these multi-dimensional multi-domain models blended into a single, unified tool providing users of these SW-GW interaction tools access to the capabilities of all XMS systems.

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