CHALLENGES AND APPROACHES IN THE DEVELOPMENT OF A REGIONAL-SCALE, FIRST-PRINCIPLE, AND PHYSICS-BASED WATERSHED MODEL FOR SOUTH FLORIDA WATER MANAGEMENT AND ECOSYSTEM RESTORATION

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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. To achieve this, it is desired to develop a regional-scale watershed model that is first-principle, physics-based, and capable of evaluating various water management alternatives for ecosystem restoration. Such a Regional Engineering Model for Ecosystem Restoration, REMER, will cover most of the South Florida area that is over 8,000 square miles, extending from north of Lake Okeechobee south to Florida Bay, and from the Atlantic Coast to the Gulf of Mexico. It will contain various hydrologic processes and features, such as 1-D canal flow, 2-D overland flow, 3-D subsurface flow, surface-subsurface interaction, rule-controlled canal structures, rule-controlled pumping across dimensions, *e.g.*, from 1D canal to 2D overland, stormwater treatment areas, lakes, levees, culverts, major roads, bridges, etc. The US Army Engineer Research and Development Center is contracted to develop the REMER model for South Florida and is expected to accomplish model calibration and validation in Year 2006. This paper provides an overview of the up-to-date status of the REMER model, including some background information of the conceptual and the mathematical models, the challenges to face, and the approaches to overcome difficulties encountered during model development. The paper also describes the generation of unstructured finite element meshes with multimillion nodes by using a renovated stitching method in the DoD Groundwater Modeling System (GMS),the parallel algorithms implemented in the parallel WASH123D code, and the model calibration-validation strategy.

BACKGROUND

This development of the REMER model is sponsored by US Army Corps of Engineer, Jacksonville District. The objective of the REMER modeling effort is to develop an engineering model to help the evaluation of the surface and subsurface flows and their interaction in the areas considered in CERP. This model will be defendable and a robust state-of-the-art numerical model that takes advantage of present day technology and capability to more thoroughly address and assess the multiple-interests and demands being placed on the management of South Florida water resources and ecosystem. The fully-coupled REMER application of the WASH123D numerical model [Yeh et al., 2003] will address the engineering and ecosystem hydrologic needs and requirements for an appropriately balanced and sustainable South Florida by modeling the significant hydrologic processes active within the model domain (Figure 1). The domain encompasses 8,000+ square miles, extending from north of Lake Okeechobee south to Florida

Bay, and from the Atlantic Coast to the Gulf of Mexico. This regional engineering model will be used to assess alternative evaluations from a regional perspective, scalable for sub-regional and project models and be linkable to ecosystem models. REMER will be a pure physics-based engineering model that incorporates up-to-date knowledge of watershed hydrology. While the operational movement of water is an integral part of REMER, the model is not intended to be used as a water distribution model. As such, REMER will be able to support other models such as water distribution models by identifying the importance and significance of any simplifying assumptions or empirical aspects of those models. REMER could then be used to help identify the important parameters that either should be maintained or can be simplified with minimal impact to the true reproduction of system processes and important system responses. The model could then be "tuned" to simplify the system and governing equations within acceptable and quantifiable limits. This approach will allow planners, operators, and managers to access to information needed to balance the desired accuracy of solution and efficiency of computation. It will also allow one to quantify the quality and accuracy of results while providing the means and flexibility to more easily modify the developed tool to meet specific modeling and field requirements.

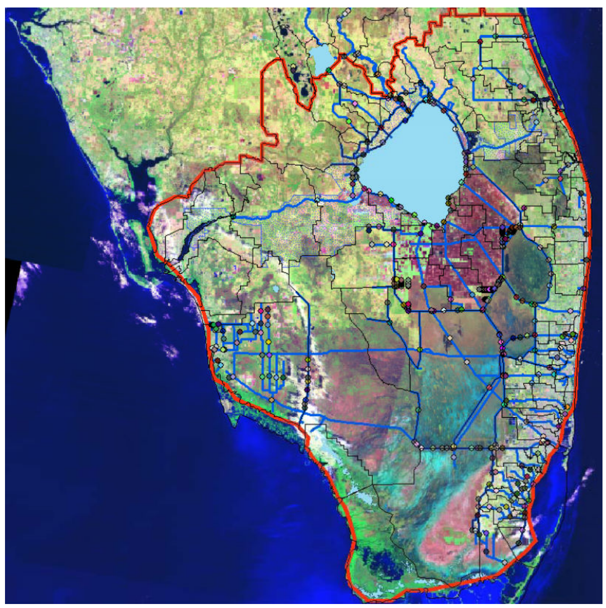

Figure 1 - The domain of REMER

WASH123D CODE

WASH123D is a physics-based, unstructured finite element model. It is designed to simulate flow, and chemical and sediment transport in watershed systems. In modeling the flow of a coupled 1-D channel, 2-D overland, and 3-D subsurface system, WASH123D integrates several components, including solving the 1-D and the 2-D diffusion wave flow models with the semi-Lagrangian approach, solving 3-D Richards equations with the Galerkin finite element method, and accounting for interactions between different media (between 1-D and 2-D, 2-D and 3-D, and 1-D and 3-D) 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., 2003].

MAJOR TASKS FOR MODEL CALIBRATION AND VALIDATION

To obtain a calibrated and validated REMER model, there are several critical technical tasks that must be performed. They are briefly described as follows.

Data Acquisition and Evaluation

This task will compile and evaluate all data needed for the regional model. The data are the basis from which the model is developed and calibrated. The data required for the modeling effort consist of two types of data; spatial data that is assumed not change over the modeling time periods (e.g., topography, hydrography, canal networks, etc.) and time series data for specific spatial locations (e.g., rainfall, surface water elevation, groundwater head, pumping rate, etc).

Conceptual Model Development

Both a geologic and a hydrologic conceptual model for the entire model domain have been developed by US Army Corps of Engineer, Jacksonville District. The geologic conceptual model will translate the hydrostratigraphy to model layers and the hydraulic properties of each layer will be assigned aquifer parameters. The hydrologic/hydraulic conceptual model will define the physical and management processes that will be included in the model. This task also includes the development of the initial and boundary conditions, periods of record to be used for model calibration and validation, aggregation of subscale processes, representation of management and operations in the model, and calibration and validation targets.

Model Development

This task includes the development of the numerical mesh that involves the discretization of the coupled system of canal network (1-D), overland (2-D), subsurface (3-D), lake, stormwater treatment area, i.e., STA, and reservoir (0-D). The numerical mesh development also incorporates important hydrological features such as canal dikes, major roads, culverts, etc., that may significantly impact flow patterns.

Model Code Enhancement

To achieve model calibration/validation for REMER, it is essential to have all important hydrologic processes and features incorporated into the numerical code of WASH123D. Enhancements in the WASH123D graphical user interface (GUI) and the parallel code are also MUST for achieving multi-million-node simulations.

CHALLENGES AND APPROACHES

The four critical technical tasks mentioned above are strongly correlated. Among these tasks, new methodologies have been proposed to deal with the challenges that come along with the REMER modeling work. The following describes these challenges and the associated proposed approach.

Challenge 1. Mesh Generation and Solution Presentation

The REMER project, due to the extensive physical requirements and large geographic domain, will require a computational domain composed of millions of finite elements and nodes. Construction of such a large model poses several computational challenges. Parameterization of the model within the DoD Groundwater Modeling System (GMS, http://chl.erdc.usace.army.mil/software/gms) is performed using the conceptual modeling approach wherein boundary conditions, hydraulic and hydrogeologic properties and sources/sinks for a simulation are assigned to conceptual model objects such as arcs, nodes, points and polygons. These same conceptual objects are also used to construct the finite element mesh, including 1-D canal network, 2-D overland, and 3-D subsurface, which enables the parameters to be transferred to the computational domain via a mapping function. This method allows parameters for large simulations to be stored and applied in an efficient and convenient fashion. However, constructing and holding a multi-million node finite element mesh in memory in a graphical user environment such as GMS, requires computational resources that stretch the design limits of GMS and, more critically, exceed the memory limitations of the current 32-bit or the future 64-bit operating systems on which GMS runs.

Overcoming this mesh construction limitation requires a “divide and conquer” approach similar to that employed in parallel processing applications. A conceptual model exists for the entire REMER domain. However, when the conceptual model is used to construct the finite element mesh, the mesh domain is constrained to a small portion of the overall domain. In this fashion, “submodels” are created to which the conceptual model parameters are mapped and the simulation saved. Once saved, that simulation is cleared from memory and the process is repeated for each subsequent “subdomain.” The result is a set of submodels that, in piece-wise fashion, define the complete simulation. The submodel simulations are then stitched together by means of intelligent functions that eliminate duplicated boundary nodes into a single set of simulation input files for the entire REMER domain. Figure 2 depicts an example of breaking the entire REMER model into five submodels (i.e., SD-1 through SD-5).

The same issues that restrict the construction of such a large simulation affect the post-processing of simulation results as well. After execution in the HPC environment, simulation results are split into corresponding submodel results files that can be read in and post-processed in GMS in single and small group fashion. Additionally, to facilitate the post-processing of the simulation results in an overall fashion, a coarse version of the mesh and simulation results are created that do not exceed the operating system limitations.

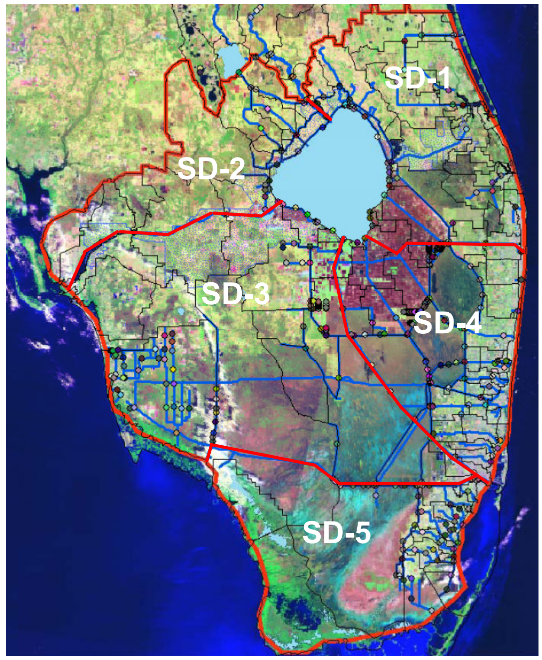

Figure 2. An example of breaking the entire REMER domain into subdomains

Challenge 2. Run Time

It can be anticipated that a tremendous amount of computation is involved in REMER model calibration and validation. To conduct as many simulations as possible within a fixed period of time, running WASH123D on multi-processor high performance computing (HPC) machines is a MUST. In WASH123D, various numerical approaches are implemented to solve different components of the coupled system [Yeh, et al., 2003]. The parallelization of such a complex model starts with the data structure design and then tackles the programming paradigm. The original serial computational kernel is preserved to shorten the development time, because there is no parallelization involved. Tasks in this area include data structure design, software tool integration, and software tool development. Figure 3 sketches each of three objects (WashMesh) and embraces each component under the entire computational domain (WashDomain). Each object (i.e., WashMesh) is partitioned based on users' partitioning criteria, to processors by **Dbuilder** [Hunter and Cheng, 2004]. **DBuilder** also provides a coupler, which encapsulates all the implementation of communication/synchronization schemes between different WashMesh objects.

In order to solve the 2-D overland flow problem, the parallel particle tracking (PT) software is facilitated with a new pathline computational kernel to accurately track particles under unsteady flow fields [Cheng and Plassmann, 2004]. Based on the lightweight functional interface that PT provides, the PT software is then easily integrated with the parallel WASH123D. The software tool DBuilder is served as a parallel programming environment, which calls ParMETIS (Parallel graph partitioning, http://www.users.cs. umn.edu/~karypis/metis/parmetis/) to partition the domain, encapsulates all the MPI implementation to maintain coherent data among processors, and coordinates coupled applications. With such a coupler object built by DBuilder, the dependency between meshes can be neglected when partitioning.

Challenge 3. Approach of Model Calibration and Validation

A major concern in the model calibration and validation of a coupled 1-D/2-D/3-D system is model run time. When all the features and complexities are included in a coupled regional-scale 1-D/2-D/3-D watershed model for calibration and validation, each model run will have to embrace solving not only individual 1-D, 2-D, and 3-D nonlinear flow equations but also a nonlinear coupled system that accounts for 1-D/3-D, 1-D/2-D and 2-D/3-D interactions, which will make each model run time consuming when a large mesh (e.g., multi-million nodes) is considered for a simulation time that is not short even though the parallel code is employed (it has been decided that the REMER model will be calibrated by using the observed data from a wet and a dry rainfall years and validated from an average rainfall year, where the wet and dry rainfall years are chosen from the past 20 years to represent two extreme cases). As a result, the calibration/validation result might not be satisfactory when only a limited time is given. To produce a better calibration/validation model, a more efficient approach that includes four steps is proposed. The four steps are: calibrating the coupled 2-D/3-D flow model for each subdomain; validating the coupled 2-D/3-D flow model for the entire REMER domain; calibrating the coupled 1-D/2-D/3-D flow model for each subdomain; and validating the coupled 1-D/2-D/3-D model for the entire REMER domain. They are briefly described as follows:

Step 1. Calibrating the coupled 2-D/3-D flow model for each subdomain. In this step, the calibration parameters include Manning's roughness coefficients of 2-D overland flow and hydraulic conductivities of 3-D subsurface flow given the soil curves for the unsaturated zones. To account for the canal/subsurface interaction, the observed 1-D canal stage is applied at the corresponding 3-D subsurface nodes and serves as head-type boundary condition. As for taking into account the 1-D/2-D interaction, there is no interaction between the canal and the overland waters, and a zero depth is applied to the dike-corresponding overland nodes when the canal dike exists. On the other hand, at canal banks where 1-D/2-D interaction may occur if dikes are not installed, the observed canal stage is applied to the bank-corresponding overland nodes when the canal stage is higher than the elevation of the overland nodes, and a downstream rating curve boundary condition when canal stage is below the overland nodes. The overland nodes that are used to represent drainage divide for overland flow (e.g., major roads and mountain peaks) can also be treated as interior boundary nodes where a zero-depth boundary condition is applied. By using the observed canal stage as the boundary condition for the coupled 2-D/3-D subdomain model, the most accurate and complete data is used in calibrating overland Manning's roughness coefficients (n2) and subsurface hydraulic conductivities (K), and quick turn-around time for each subdomain simulation will be received. It is determined that one subdomain will be separated from its neighboring subdomains by canals which provide definite flow boundary conditions for both surface and subsurface systems. The calibration for a subdomain can be independent of those of other subdomains. In other words, the calibration of all subdomains can be executed in parallel.

Step 2. Validating the coupled 2-D/3-D flow model for the entire REMER domain. In this step, the entire coupled 2-D/3-D flow model is constructed by using the stitching program mentioned above to not only generate the entire REMER domain mesh but also the needed model information for simulations. The calibrated n2 and K obtained from Step 1 will be fixed, and simulations for the three water years selected for model calibration and validation will be used. Since canal stage is still used as the boundary conditions for the entire coupled 2-D/3-D model, it is expected to complete this step without spending much time in further adjusting K and n2.

Step 3. Calibrating the coupled 1-D/2-D/3-D flow model for each subdomain. The main purpose of this step is to calibrate the canal Mannning's roughness coefficients (n1) for the canals considered in each subdomain. The K and n2 obtained from Step 2 are used and stay unchanged for all the simulations conducted in this step.

Step 4. Validating the coupled 1-D/2-D/3-D model for the entire REMER domain. Through Steps 1, 2 and 3, all the model parameters (i.e., n1, n2, and K) are calibrated for each subdomain. The only model parameter that has not been calibrated is n1 of the canals that separate the subdomains. Therefore, in this step, the main purpose is to calibrate the missing n1 and get the entire coupled 1-D/2-D/3-D model validated. Since the n1 to be calibrated in the step is limited, the simulations conducted in this step should not be many.

It has been determined that mean absolute error (MAE), root-mean-square error (RMSE), and/or coefficient of efficiency (or Nash Sutcliffe Forecast Efficiency, N-S) will be used as error measures for model calibration and validation. In Steps 1 and 3, short-term simulations (e.g., 2-3 months) will be conducted first to help speed up the calibration process.

SUMMARY

The REMER model is designed to compute surface and subsurface flows and their interactions for the CERP project area. It will help address the engineering and ecosystem hydrologic needs and requirements for an appropriately balanced and sustainable South Florida by modeling the significant hydrologic processes active within the model domain. The model employs the physics-based, unstructured finite element model, WASH123D, as the computational kernel. Several critical tasks have been identified in order to achieve model calibration and validation. Three challenges in the REMER development were also identified. A "divide and conquer" approach and DoD GMS are employed to perform mesh generation and solution presentation at various levels of mesh size. The approach to construct the WASH123D parallel code is presented to tackle the computational time issue, where the software tool **Dbuilder** has been developed to perform both partitioning and coupling for the unstructured mesh. To effectively calibrate and validate the REMER model, a four-step approach has been developed to allow more model runs conducted for successful model calibration and validation. Some large-mesh testing result to demonstrate the success of the stitching program and parallel WASH123D at the conference.

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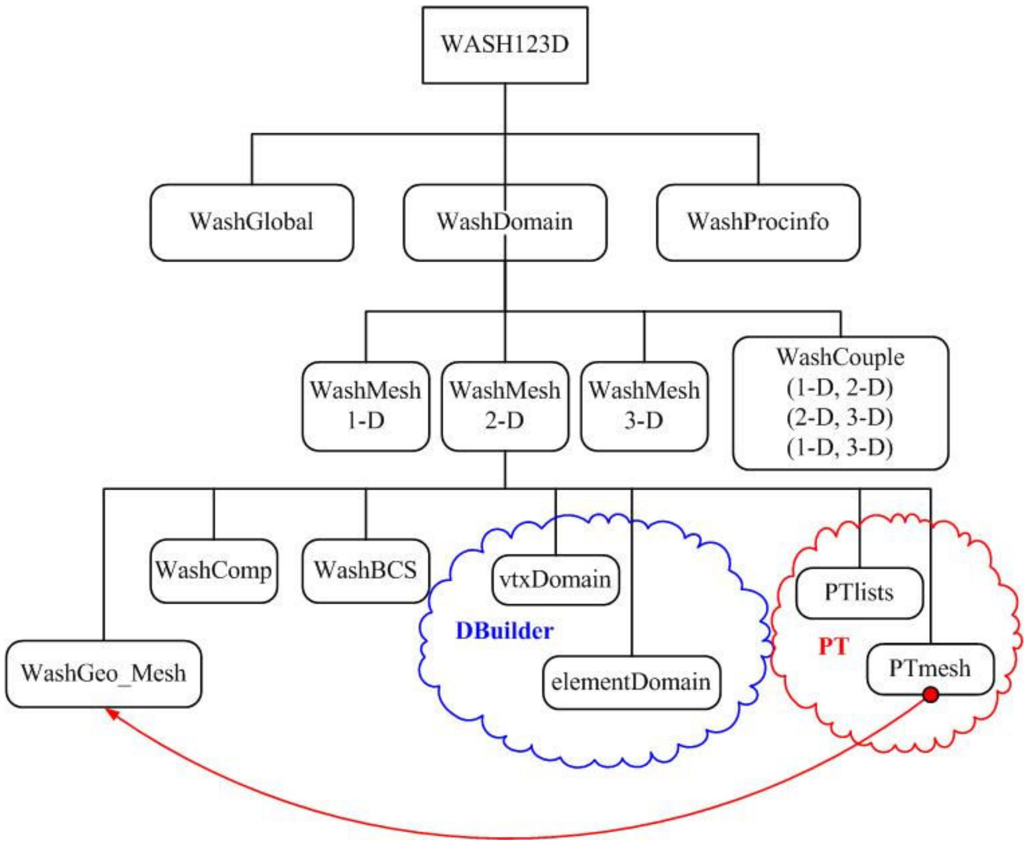

Figure 3. Data structure design of the parallel WASH123D