Developing a Regional Engineering Model for 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. Although CERP is comprised of 68 major components, which are grouped into over 40 projects, it is desired to construct a Regional Engineering Model for Ecosystem Restoration (REMER). The REMER model covers most of the South Florida area and contains various hydrologic processes and features, such as 1-D canal flow, 2-D overland flow, 3-D subsurface flow, canal control structures, surface-subsurface interaction, pumping wells, retention ponds, lakes, levees, culverts, roads, bridges, etc. The US Army Engineer Research and Development Center, ERDC, has been contracted to develop the REMER model for South Florida and is expected to accomplish model calibration and validation in Year 2006. This paper will provide an overview of the REMER model that includes the background information and the five critical technical tasks. It will also address challenges anticipated in the model development, including graphic user interface, GUI, development, computational code parallelization, and model calibration and validation approach.

Background

Ongoing efforts to plan and design the initially authorized projects under CERP have reconfirmed the critical need for accurate, predictive numerical models capable of simulating the complex hydrologic and hydrodynamic processes at work in southern Florida on local, regional and system-wide scales. A need exists for a flexible and powerful engineering modeling tool capable of addressing detailed hydrologic and hydraulic processes using first principles of physics (Yeh, 2003a) at a range of scales.

The objective of the REMER modeling effort is to develop an engineering model for the evaluation of the surface and subsurface flows and their interaction for the CERP project area. 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., 2003b) 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 about 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, this 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.

WASH123D. WASH123D is a physics-based, unstructured finite element model. The model 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. They are (1) solving the 1-D and the 2-D diffusion wave flow models with the semi-Lagrangian approach, (2) solving 3-D Richards equations with the Galerkin finite element method, and (3) 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., 2003b).

Tasks

In order to meet the aggressive schedule of having a calibrated and validated model by June of 2006, it will be necessary to deviate from the standard sequential model development process and adopt a parallel development approach. There are several critical technical tasks that must be performed in parallel or with significant overlap to meet the June 2006 deadline. 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 and time series data for specific spatial locations.

The spatial data is used to simulate in the model the real world features. Probably the single most important aspect of the spatial data is the development of the geologic model. This includes identifying the various aquifer and aquitard layers, the hydrostratigraphy of each layer, and their hydraulic parameters, such as the vertical and horizontal hydraulic conductivity and leakance. The spatial data also consist of the topography of the model domain and hydrography, which consist of lakes, rivers and other surface waters, anthropogenic features, and land use or land cover. Other important aspects of the spatial data are the network of canals within the model domain, public and private water supply information, and hydraulic structures, along with the hydraulic properties associated with the structure.

The time series data are used to establish the boundary condition, which drives the model, and is also used to calibrate and validate the model results. This data consist of precipitation, potential evapotranspiration (ET), canal discharge and stage, overland stage, groundwater elevation, tidal data, and salinity data. Included in the time series data are the various hydraulic structure operations, such as gate openings or pumping schedules. This data also include regulation schedules and lake stages.

Both the spatial and time series data are obtained using various sources. The majority of the spatial data such as the canal network and the hydraulic properties associated with the structures is provided by US Army Corps of Engineer, Jacksonville District. The Jacksonville District will also provide some of the time series data, such as the hydraulic structure operations, gate openings, and pumping schedules. The topography is obtained from LIDAR data that is the acronym for Light Detection And Ranging. The public and private water supply information is obtained from water usage permits, which were gathered for the SFRSM, SWFRS and C44 projects. The time series data is obtained from the SFWMD website known as DBHydro (http://www.sfwmd.gov/org/ema/dbhydro/index.html). This website has the daily data of precipitation, ET, canal flow and stage, groundwater elevation, tide, and salinity.

Conceptual Model Development. Both a geologic and a hydrologic conceptual model for the entire model domain will be developed. 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.

Canal Structure Rating Curves and Operational Rules. This task will involve the understanding and development of the operational rule and the associated rating curve for Lake Okeechobee and for all primary and major secondary canal structures. The operational rules and rating curves will be incorporated into the WASH123D numerical model.

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 input and model computation issues such as time interval, canal structure operation, and inter-dimensional pumping, are also addressed in this task. The other major component included in this task is model calibration and validation.

Model Code Enhancement. To achieve model calibration/validation as well as future applications with the REMER model, it is essential to have all the canal structure rules, inter-dimensional pumping controls, and 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 necessary.

Challenges and Approaches

The five 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 several 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, 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 32-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 mesh broken into submodels.

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.

Challenge 2. Computational Time. It can be anticipated that a tremendous amount of computation is involved in the REMER model runs. To conduct model runs efficiently, using the parallel computational code is a MUST. In WASH123D, various numerical approaches are implemented to solve different components of the coupled system. 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**. **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. 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.

To perform long-term simulations on the high performance computing (HPC) machines, it is also desired that a hot start feature be made available in the parallel WASH123D.

Challenge 3. 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., several 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 available. To produce a better calibration/validation model, a more efficient approach is needed. An approach that includes four steps, calibrating the coupled 2-D/3-D flow model, calibrating the 1-D flow model, verifying the calibrated model obtained from the previous two steps, and validating the coupled 1-D/2-D/3-D model, is proposed in order to conduct more model runs and hopefully produce a better calibrated and/or validated model. The four steps are briefly described as follows:

<u>Step 1. Calibrating the coupled 2-D/3-D flow model.</u> 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 3-D subsurface boundary nodes that are corresponding to 1-D canal nodes (highlighted in blue color in Figure 4) are enforced to be head-type boundary nodes, where the observed time-dependent canal water stage is applied. Linear interpolation is used to determine canal water stage at a location between two observation gauges within a canal reach.

As for taking into account the 1-D/2-D interaction, the canal-corresponding overland nodes (highlighted in blue color in Figure 4) are treated as stage-type interior boundary nodes where the observed canal water stage is applied. Where canal dikes exist, there is no interaction between the canal and the overland waters, and a zero depth is applied to the dike-corresponding overland nodes (highlighted in red color in Figure 5) that are treated as interior boundary nodes for the 2-D overland flow computation. 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 (Figure 6a), and a downstream rating curve boundary condition when canal stage is below the overland nodes (Figure 6b).

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 model, we have included the most accurate and complete data in calibrating overland Manning's roughness coefficient and subsurface hydraulic conductivity.

<u>Step 2. Calibrating the 1-D flow model.</u> In Step 1, the observed 1-D canal stage is employed as given boundary conditions to calibrate the coupled 2-D/3-D flow system. In Step 2, the Manning roughness coefficient of 1-D canal is calibrated by fixing the 2-D overland and 3-D subsurface parameters (i.e., 2-D Manning roughness coefficients and 3-D hydraulic conductivities) that are obtained from Step 1 in the coupled 2-D/3-D flow system. To calibrate and validate 1-D canal flow for each reach, it is essential to have the upstream boundary condition, the downstream boundary condition, the source/sink terms (e.g., rainfall, pumping, infiltration/seepage, overland runoff) either clearly specified or estimated, so that the computational system can be closed and the computed water stage can be compared against the observed water stage at desired locations. Rainfall, pumping rate, and boundary conditions are usually determined based on field measurements. To ease the calibration of 1-D flow, time periods during which there is no overland-canal interaction are selected so that zero overland runoff can be employed. To account for canal-subsurface interaction, the computed infiltration/seepage

rate through the 1-D/3-D interface is bookmarked at the canal-corresponding 3-D subsurface nodes in Step 1 and used as a source/sink for 1-D flow computation in Step 2.

Step 3. Verifying the calibrated model obtained from Step 1 and Step 2. From Steps 1 and 2, a set of calibrated parameters, including 1-D canal Manning roughness coefficient for each canal reach, 2-D overland Manning roughness coefficient for each land use area, and 3-D subsurface hydraulic conductivity for each material type, are obtained based on desired error measures, e.g., mean absolute error (MAE), root-mean-square error (RMSE), and/or coefficient of efficiency (or Nash Sutcliffe Forecast Efficiency, N-S). In Step 3, model runs with the set of calibrated parameters are conducted to verify the calibrated model in the selected calibration periods of time. If the model is tested to be adequate, model calibration is complete. Otherwise, a different set of calibrated parameters must be chosen from Steps 1 and 2 and tested in Step 3. These steps will be repeated until a calibrated model is found.

Step 4. Validating the coupled 1-D/2-D/3-D model. Through Steps 1, 2 and 3, a coupled 1-D/2-D/3-D model is calibrated. In this step, the calibrated model is further tested with the observed data from the elected average rainfall year for validation. If the model is tested to be valid, model validation is then complete. Otherwise, one needs to select and test a different set of model parameters by repeating Steps 1 through 4. It is noted that one uses the observed wet- and dry-year data during model calibration (i.e., Steps 1 through 3) and the data of the selected average-rainfall year, which is considered independent from that of both wet and dry years, for model validation.

Summary

In essence, the REMER model will be a robust state-of-the-art tool for the evaluation of the surface and subsurface flows and their interactions for the CERP project area. REMER 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. The model will employ the physics-based, unstructured finite element model, WASH123D. Several critical tasks have been identified and must be performed in parallel or with significant overlap in order to meet the June 2006 deadline. Three challenges that will be encountered in developing the REMER model were also identified. A "divide and conquer" approach will be employed to perform mesh generation and solution presentation when a large mesh (e.g., several million nodes) is required. 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 within a limited period of time, an approach that includes four steps is proposed. This approach is developed to allow more model runs conducted for successful model calibration and validation.

Acknowledgment

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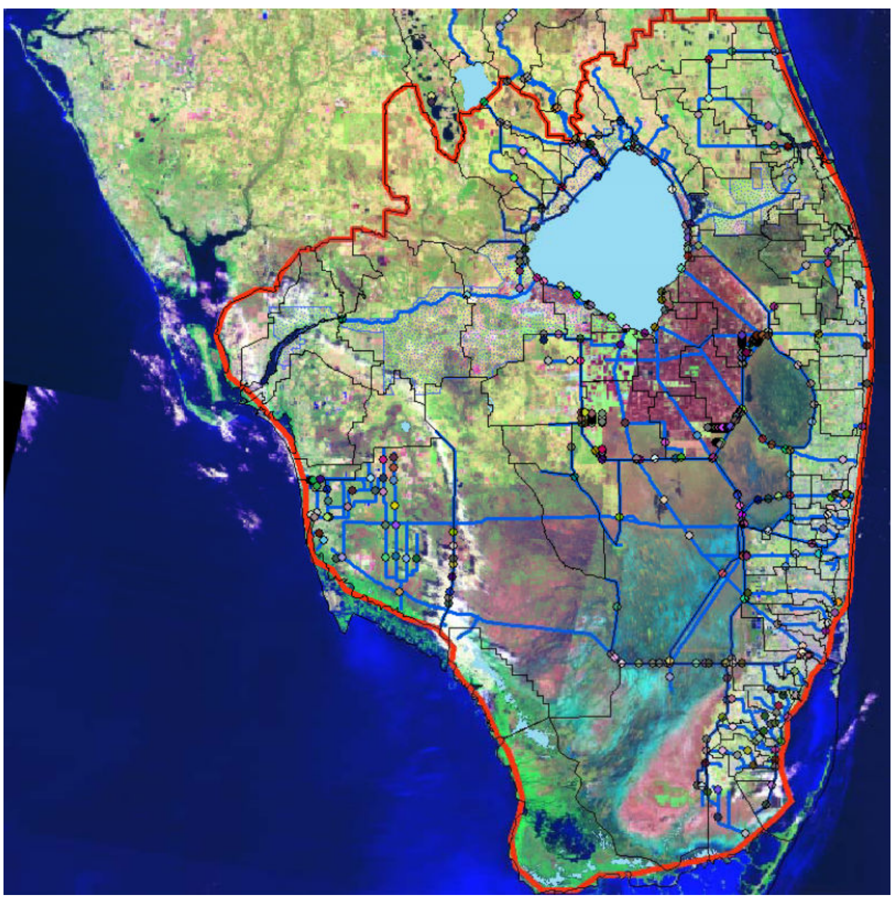

Figure 1. The domain of REMER

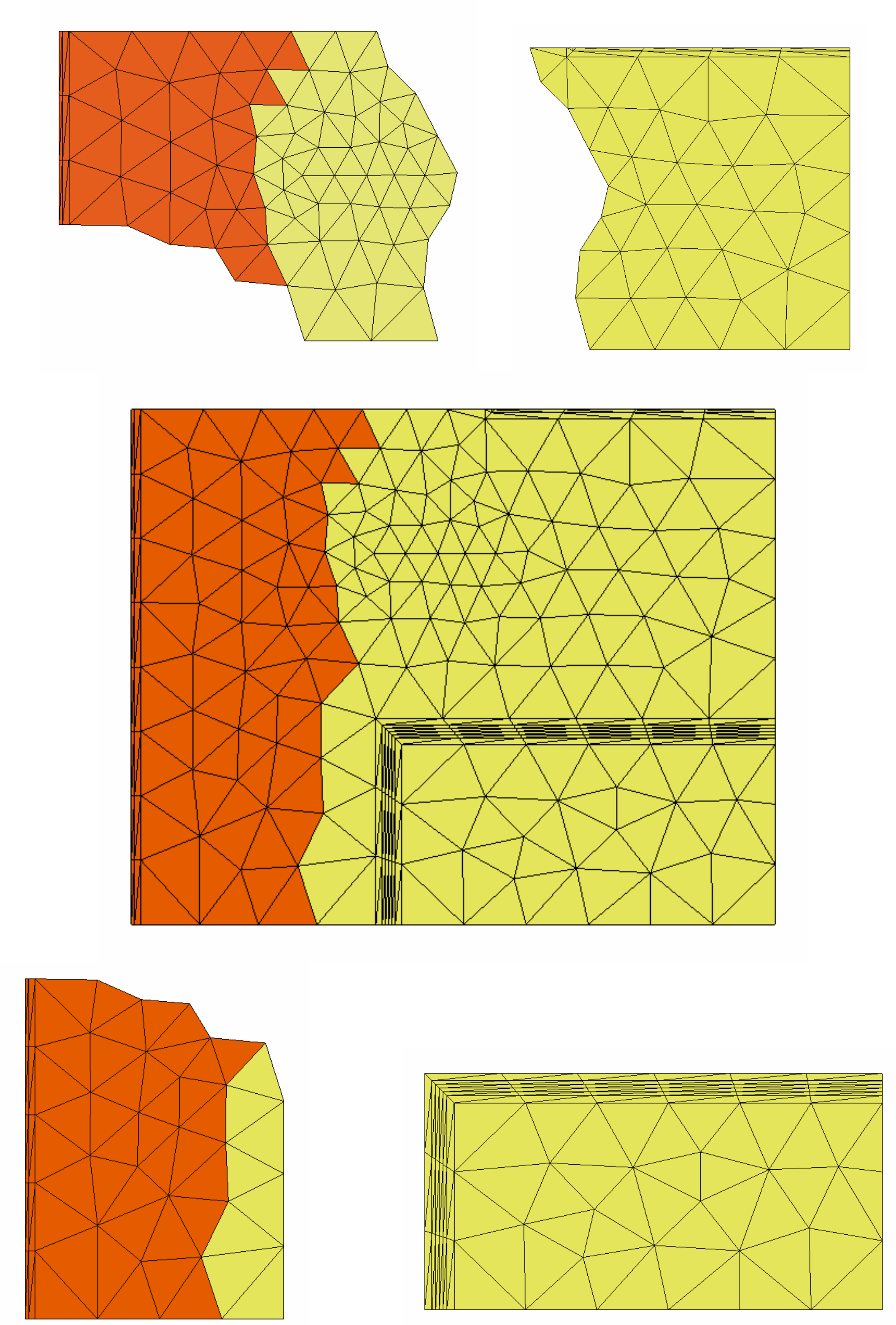

Figure 2. Four subdomains (at four corners) generated from GMS are stitched together into the complete domain (center)

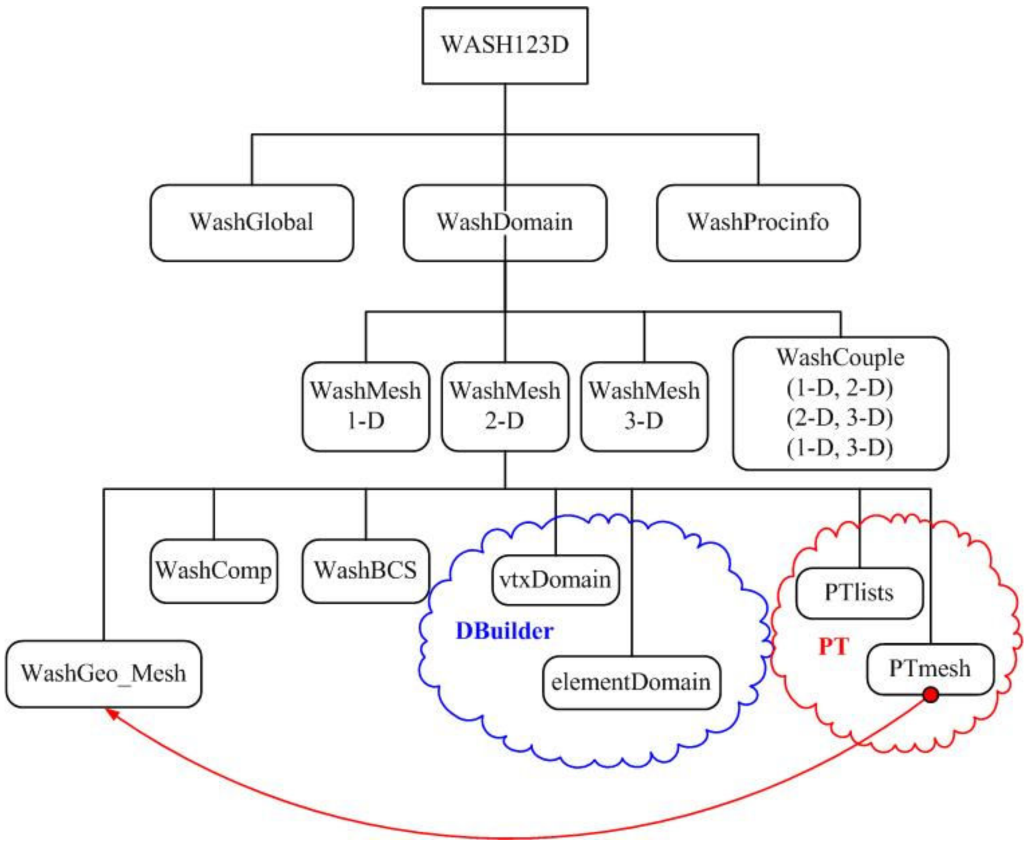

Figure 3. Data structure design of the parallel WASH123D

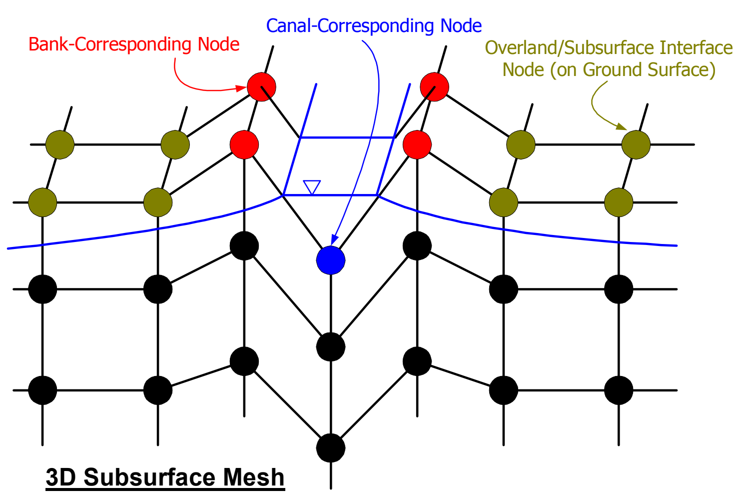

Figure 4. A sketch to highlight the canal-corresponding nodes on a 3D mesh

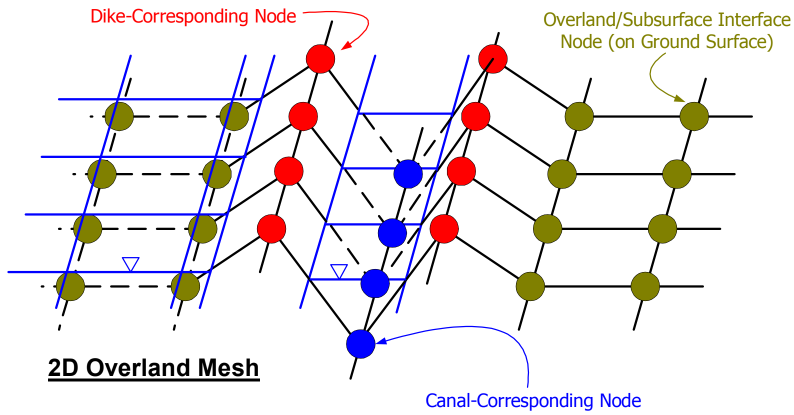

Figure 5. A sketch to highlight the canal- and the dike corresponding nodes on a 2D mesh where no interaction exists between the canal water and the overland water

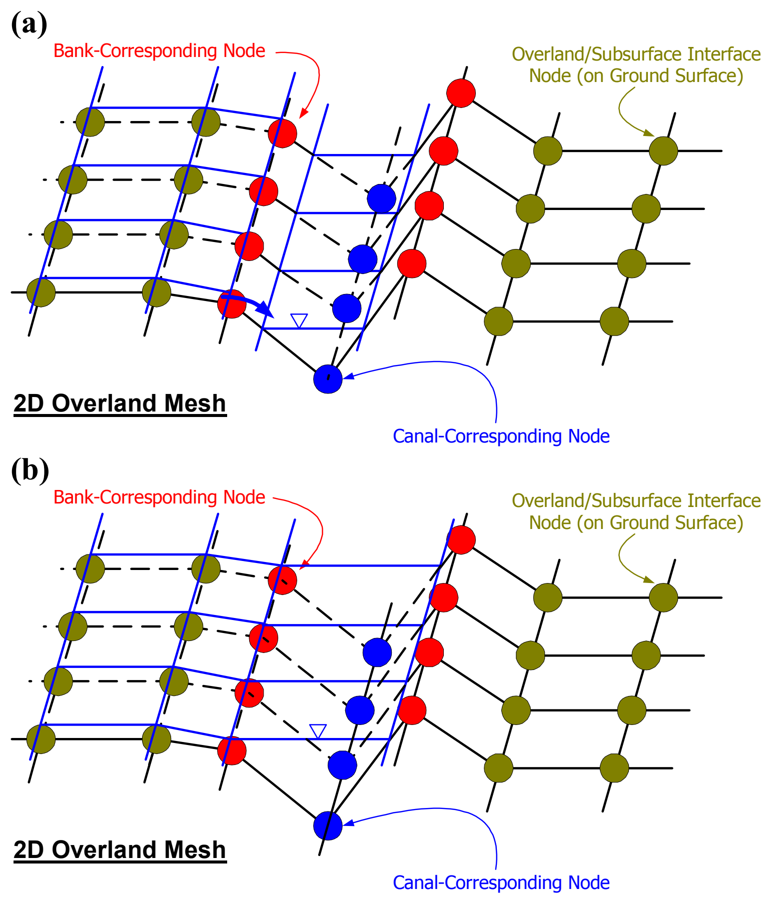

Figure 6. A sketch to highlight the canal- and the bank-corresponding nodes on a 2D mesh where interaction exists between the canal water and the overland water: (a) when the overland water and the canal water are separate; (b) when the overland and the canal water are connected