A Multidimensional Modeling System for Simulating Coupled Canal, Overland, and Groundwater Flow in South Florida

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Abstract

Given the complex nature of hydrologic process in South Florida and the flood protection works that affect the hydrologic cycle, it is essential to have hydroinformatic systems to assist decision makers. The hydroinformatic systems must contain hydrologic models that can accurately simulate physical processes at the proper time and space scales without the crude schematization that has been common in previous modeling systems. The developed hydroinformatic system includes the FEMWATER123 model supported in the Department of Defense Groundwater Modeling System (GMS). The developed model (FEMWATER123) uses the Galerkin finite element method to simulate 1-D canal flow, 2-D overland flow, and 3-D groundwater flow in a coupled manner. The canals are simulated using the 1-D diffusive wave assumption including hydraulic structures with individual operation rules that are updated at one-minute intervals. The overland areas are simulated using the 2-D diffusive wave assumption while variably saturated groundwater flows are calculated using Richards equation. Results from the South Florida application are presented.

Introduction

The Jacksonville District (SAJ), US Army Corps of Engineers and the South Florida Water Management District (SFWMD) have joint responsibility for managing the water resources of South Florida. These responsibilities include operating the extensive flood protection works and canals that significantly affect the surface and groundwater hydrology of the region. While these flood protection works have served their purpose adequately over the years, there has been an effort recently to revisit their design with the hope of returning the environment back to a more natural state. This is a difficult task since this means raising water levels and thereby increasing flood risk. In addition to this dilemma, there are competing interests for the use of the water. Everglades National Park needs water for ecological reasons, agricultural interests need water to develop their businesses, and municipalities have increasing populations that want a clean water supply, recreational facilities, and flood protection at the same time. Given this complicated and challenging public environment, management decisions that affect water resources are very difficult to make and therefore require a thoughtful political process backed up with accurate scientific and engineering analyses.

Hydroinformatic Systems

In this environmental age, it is essential to have hydroinformatic systems to assist decision-makers (Richards & Jones, 1996). The hydroinformatic systems must contain hydrologic models that can accurately simulate physical processes at the proper temporal and spatial scales. The systems must also be efficient in the sense that model development, setup, and execution can be attained in reasonable periods of time. Innumerable management scenarios will be simulated to obtain the proper optimization of flood control and environmental benefits. Numerical modeling systems are already being used in South Florida to make regional analyses of various projects, including the venerable "2x2 model", a finite-difference model based on 3.2 km by 3.2 km (2-mile by 2-mile) cells (MacVicar, et al., 1984). These models have typically relied on simplifications of hydrologic processes necessitated by numerical difficulties and the availability of sufficient computing power. However, they have been useful in making regional characterizations of different management plans. Once the regional studies have been made, the next step in the management process is to develop designs for projects that will be constructed. This requires numerical modeling improvements to provide a greater level of accuracy than that provided by current modeling approaches.

Multi-dimensional Model

The numerical modeling improvements that are needed are tied to the complex hydrologic processes in South Florida and the flood protection works that complicate the hydrologic cycle in this region. Depending on the hydrologic conditions, water can quickly transform from overland flow directly to groundwater flow or from canal flow directly to groundwater flow with small changes in hydrologic conditions. Additionally, some of the proposed modifications to canal operations include pumping canal water directly to overland flow areas that ultimately lead to the coast by either surface or groundwater mechanisms. Therefore, it is essential that numerical models be able to simulate these complex conditions with some degree of accuracy. Many existing numerical models are available for modeling the simple overland or groundwater flow as uncoupled processes. When this study was initiated in 1995, no numerical modeling code available was capable of coupling 1-D canal flow, 2-D overland flow and 3-D groundwater flow. Therefore, a decision was made to develop a numerical modeling code with attributes tailored to the particular needs of the South Florida hydrologic system.

FEMWATER123/GMS

The developed numerical modeling code FEMWATER123 uses the Galerkin finite element method to simulate 1-D canal flow, 2-D overland flow, and 3-D groundwater flow in a coupled manner. The canals are simulated using the 1-D diffusive wave assumption including hydraulic structures with individual operation rules that are updated at one-minute intervals. The overland areas are simulated using the 2-D diffusive wave assumption while variably saturated groundwater flows are calculated using Richards equation (Yeh et al., 1997). The FEMWATER123 code can be run in the following combinations: 2-D overland flow, coupled 2-D overland flow and 3-D subsurface flow, coupled 1-D canal flow and 3-D subsurface flow, and coupled 1-D canal, 2-D overland and 3-D subsurface flow. Once the FEMWATER123 code was developed, the Department of Defense Groundwater Modeling System (GMS) graphical user environment (Owen, Jones, & Holland, 1996) was modified to provide support for the capabilities of FEMWATER123. Among others, these capabilities include an exhaustive list of hydraulic structure types currently in use in South Florida.

Conceptual Model

Before the code could be applied to South Florida, a hydrogeologic conceptual model was developed for the entire South Florida area. The conceptual model was designed to cover the area of interest from deep in the stratigraphy to the land surface. From this conceptualization, many smaller models could be developed to study specific problems without the need to re-conceptualize each study area again. The area conceptualized extends from about five miles north of the Tamiami Trail south to the tip of the peninsula, and from the Atlantic Ocean west to the Gulf of Mexico and covers significant portions of Dade and Monroe Counties. This area includes a wide variety of land use zones ranging from farming and housing developments to urban areas to the Everglades National Park.

Geologic Data. Borehole and surface topographic data obtained from available sources were collected and imported to GMS. Using these data and the site conceptualization tools available in GMS a 3-D conceptual model of the ground surface and the stratigraphy was developed.

Hydraulic Data. Estimates of hydraulic conductivity values for the various soil materials were based on pump test information. Thirty-one rainfall gauges and three evapotranspiration gauges were used to develop spatially distributed datasets that were used as input for the model. FEMWATER123 computes overland flow and runoff, thus eliminating the need to estimate groundwater recharge. Evapotranspiration and rainfall are input to the model directly via the same time series curve. On days where precipitation occurred, if the precipitation total was below a threshold value, evapotranspiration was subtracted from daily rainfall totals to estimate surface influx for those days.

Canal System. The South Dade County canal system consists of numerous control structures. These structures can be grouped into three different types based on their gate controls: gates with automatic control, gates with manual controls, and pumping stations. Each control structure has its own operating rule curves. The gates are controlled in accordance with specific operational criteria. The 1-D canal simulator in FEMWATER123 was designed to simulate all possible controls and scenarios currently in existence in the South Dade County canal system.

Dual Models

The main goal of the modeling investigation was to simulate the complex interactions between 1-D canal, 2-D overland and 3-D groundwater flow. However, as one moves from the west to the east across the study area, a natural separation exists between areas heavily influenced by overland flow and areas influenced more by canal flow. This separation was chosen as an ideal location for breaking the study area into two well-defined models: one model consisting of mainly the Everglades National Park (ENP) and the other covering the majority of South Dade County. Dividing the study into two parts in this fashion eliminates the need to include the 1-D canal flow calculations in the ENP model, thereby providing greater numerical efficiency. In order to ensure continuity between the two models, the boundaries of the models were chosen such that they overlapped a large area in the center of the study area (Figure 1).

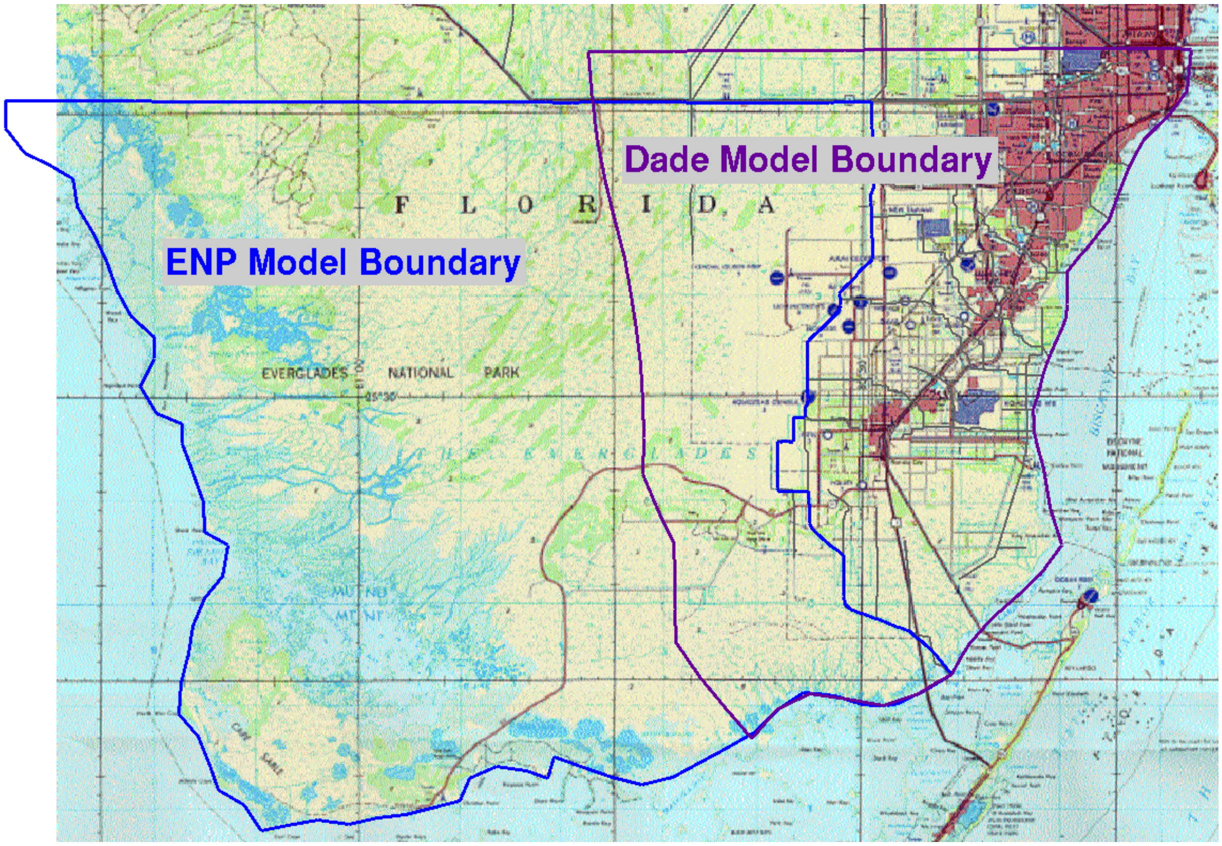

Figure 1. Boundaries of ENP and Dade Models.

ENP Model

The ENP numerical model extends from just south of the levee along the Tamiami Trail on the north to the southern coastline of south Florida, and from the western coastline of south Florida to the L-31N and C-111 canals on the east. Vertically, the numerical model extends from the land surface to the bottom of the surficial aquifer and contains the following geologic units/materials: Everglades Peat, Anastasia Formation, Lake Flirt Marl, Miami Oolite, Fort Thompson Formation, Tamiami Formation, Grey Limestone and the Hawthorn Formation. The western limit of the Biscayne aquifer falls within the domain of this model and separate materials are used to represent the corresponding lower permeability layers of Miami Oolite and Fort Thompson formation materials found to the west beyond this limit. A separate material type was used to simulate the L-67 Extension dike material as well.

Figure 2 shows the numerical mesh that was used to represent the geologic conceptual model for the ENP model. The mesh consists of 58,140 nodes and 103,796 elements contained in 11 layers of finite elements. Accompanying the 3-D mesh is a corresponding 2-D finite element mesh of 4,845 nodes upon which all overland flow and rainfall/evapotranspiration calculations are made. The 3-D groundwater and 2-D overland flow calculations are coupled with fluid fluxes being passed from one domain to the other as needed to track the flow of water throughout the hydrologic cycle.

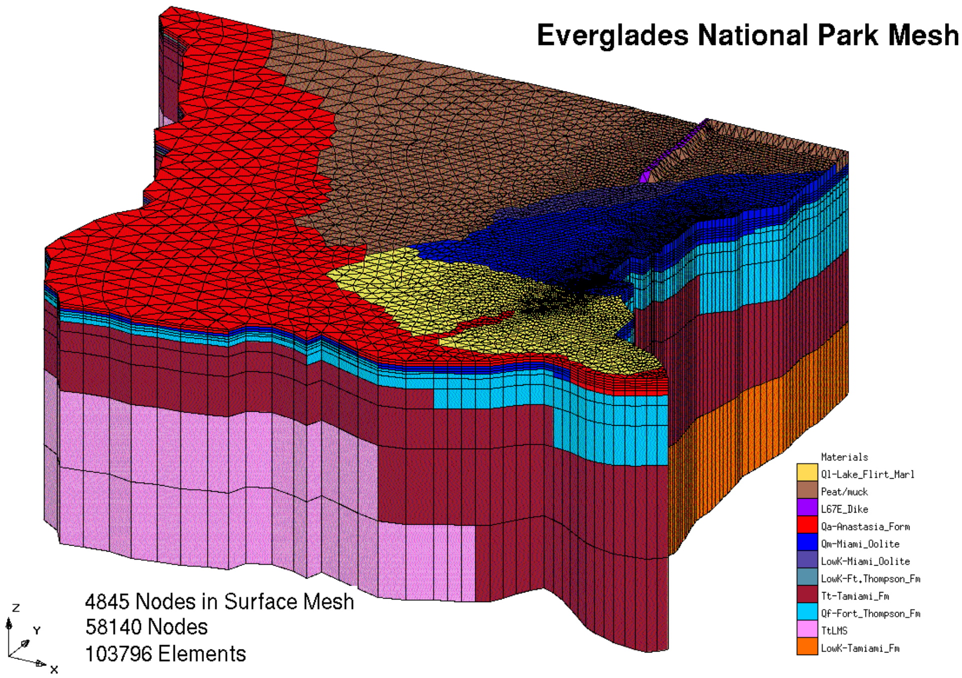

Figure 2. ENP 3-D Finite Element Mesh.

Model Boundaries. Boundaries for the ENP numerical model were chosen such that they would coincide with measured water surface elevations wherever possible. Nodes on the boundary of the ENP model that correspond to measured gages or structures are assigned the daily water level values from available data records. Between these locations, nodes of the model are assigned distanced-weighted linearly interpolated values. GMS is designed to perform this boundary condition interpolation automatically.

Model Results. Figure 3 shows the computed values for overland flow water depth for one time step across the ENP model. The surface water flow vectors are also shown. The length of the vectors indicates the relative magnitude of the flow. Comparisons between daily gage head readings and ENP model results throughout the calibration year of 1995 indicate that the model responds well to both long term seasonal and short-term rainfall and canal release fluctuations. At the various observation gages, the model response coincides in both magnitude and timing to the fluctuations in the observed record, regardless of gage location in the model. This indicates that the ENP model is able to accurately simulate response of the complex overland and groundwater flow regime found in the ENP. By coupling the 2-D and 3-D computational domains, a reliable model for evaluating impacts of proposed changes to the hydrologic system in and around the ENP has been created.

South Dade Model

The South Dade area presents numerical modeling challenges that are not found in the ENP model. While the ENP area has a very thin vadose zone and has little surface relief, the South Dade area has a thicker vadose zone that is more widespread and has greater vertical relief, particularly in the coastal ridge area. When coupled with the numerous canals and hydraulic structures in the South Dade area and the high hydraulic conductivity of the subsurface, the hydrologic simulation problem becomes much more complex than the ENP model.

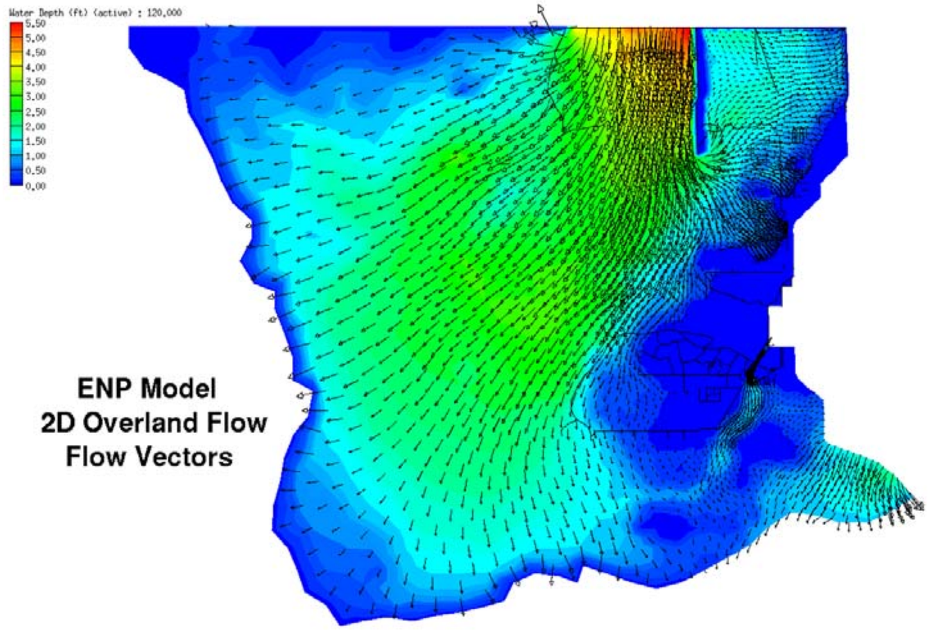

Figure 3. Overland Flow Model Results for ENP Model.

The South Dade model extends from 6.44 km (4 miles) west of the L-67 Extension dike to the western shore of Biscayne Bay and from 5.23 km (3.25 miles) north of the Tamiami canal south to Florida Bay. Vertically, the model extends from the land surface to the bottom of the surficial aquifer.

1-D Canal Network. For modeling purposes, the canal system consists of all major canals in South Dade County. Inflows to the canal system are from two structures at the top of the model. The outflows from the canal system are from a set of structures on the eastern shore and from a structure on the southeastern shore (Figure 4). All the structures in the canal system are defined at canal nodes. The junctions and dead ends of the canals are also defined at canal nodes. A canal reach is defined as a canal section between two canal nodes. Each canal reach contains many canal elements. The length of each canal element is about 610 meters (2,000 feet). Canal stages are computed based on the inflow and outflow to the system by routing canal flow using the diffusive wave method. The inflows and outflows from the canal system are computed based on canal operational rules described above. The required data include canal geometry, submerged gate rating curves at the structures, and operational criteria.

2-D Surface Mesh. The 2-D overland flow mesh consists of 4720 nodes. It is comprised of the surface layer of nodes and elements in the 3-D mesh. The 2-D mesh describes the land surface based on the best available surface topography.

3-D Groundwater Mesh. The 3-D finite element mesh that comprises the South Dade model consists of 37,760 nodes and 65,429 elements distributed over 7 layers (Figure 5).

Boundary Conditions. The boundary conditions for the canal flow equations are specified at the upstream and downstream ends of the canal system. The upstream boundary conditions are specified with a time-dependent flux profile (inflow to the canal system). The downstream boundary conditions are specified with a time-dependent stage profile.

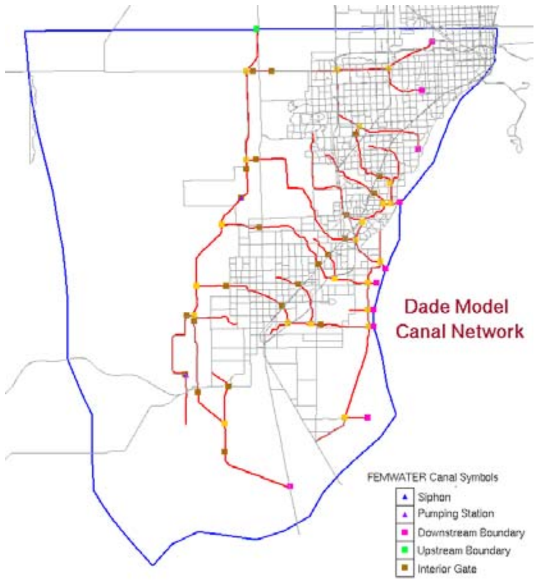

Figure 4. Dade Model Canal Network.

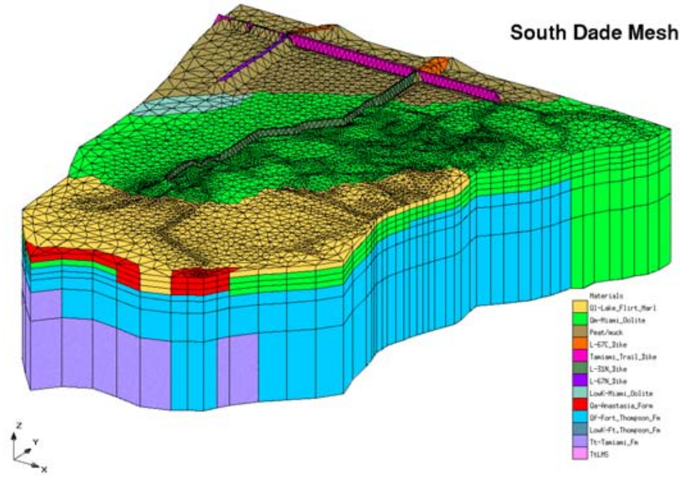

Figure 5. Dade Model 3-D Mesh.

Head boundaries for the groundwater model were selected based on the measured water surface elevations of the existing canal structures in the eastern and southern boundaries of the mesh and the groundwater level gages in the western boundaries of the mesh. On the northern boundary, no groundwater level gages are available; therefore the head boundaries were based on 2x2 model results. Between these observed gages, the heads at nodes along the boundaries are assigned based on linearly interpolated values

Model Results. Initially the model was run in coupled 2-D-3-D mode. After producing reasonable responses based on the coupled 2-D overland and 3-D subsurface flow simulation, initial conditions were saved and used as input to simulations coupling 1-D canal flow, 2-D overland flow, and 3-D subsurface flow. These simulations are the most rigorous of the simulation options and took significant computer resources for a number of reasons. Adding 1-D canals provides far more computational burden than that attributable to 1-D calculations alone. The dynamic interaction between 1-D diffusive wave canals with one-minute structure operational updates and the 3-D subsurface results in dramatic computational penalties. This coupling essentially prohibits the running of this simulation type on workstation class machines. Parallel supercomputers are necessary for all but the shortest of simulations and will continue to be so for the near future unless substantial changes are made to the code or the way simulations are made. Such changes could include changing the way rainfall and seepage boundary conditions are handled in general and the amount of rigor carried with unsaturated flow simulation in dry land areas.

The water depths and flow vectors from the overland flow simulation are shown in Figure 6. As with the ENP model, results indicated that the Dade model responded well to both short- and long-term fluctuations in water levels due to rainfall and seasonal changes in the hydrologic system of South Florida.

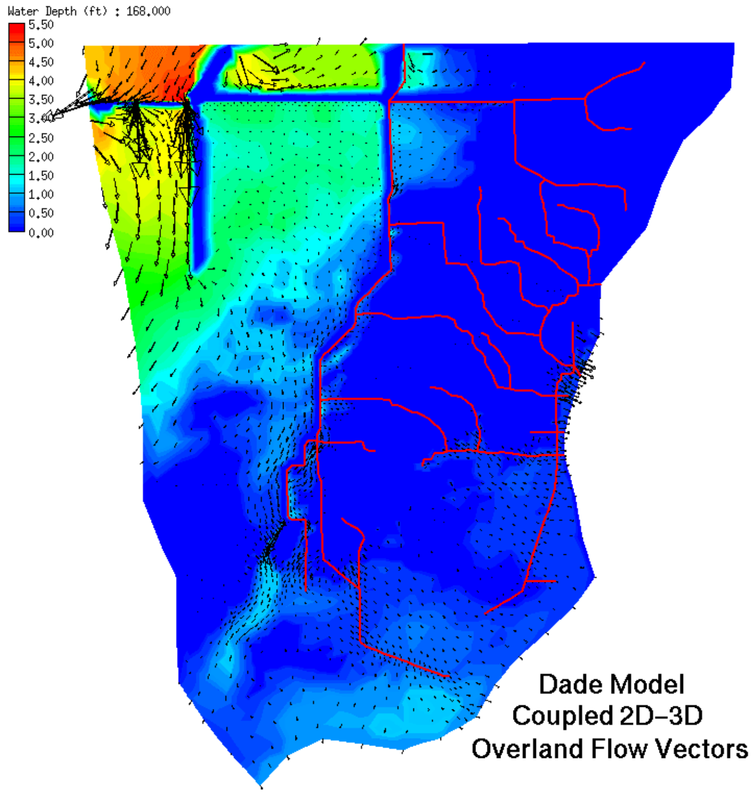

Figure 6. Water Depths for Dade Model from 2-D Overland Flow Simulation.

Recent Scenarios

The ENP and Dade models have been shown to accurately reproduce current conditions during long-term simulations of varied hydrological conditions (Lin et al., 2000). Recent studies have been undertaken to demonstrate the capability of FEMWATER123 in assessing the impacts of proposed changes to the complex South Florida hydrologic system. Two scenarios were chosen from the list of planned projects found in the *Comprehensive Everglades Restoration Plan (CERP)* (USACE-SAJ and SFWMD, 2000) and applied to the ENP model. The chosen scenarios involve backfilling of canals, modification and removal of existing levees and the addition of passive weir and other water control structures to existing levees. These modifications are designed to restore sheetflow, reduce unnatural discontinuities, and add conveyance between disconnected areas in order to help re-establish natural hydroperiods and hydropatterns in the system (USACE-SAJ and SFWMD, 2000).

Model Expansion. Some of the modifications in the chosen scenarios involved canals and structures that are found either at the boundary or beyond the extent of the existing ENP model. In order to evaluate the impacts of the proposed changes to the system, the ENP model had to be expanded (see Figure 7). The conceptual model of the South Florida subsurface stratigraphy already included a large portion of the area to be added and was further expanded to include all of the additional study area. Additional hydrologic and boundary canal stage data were identified and collected along with 2x2 model results to generate boundary conditions for the expanded model.

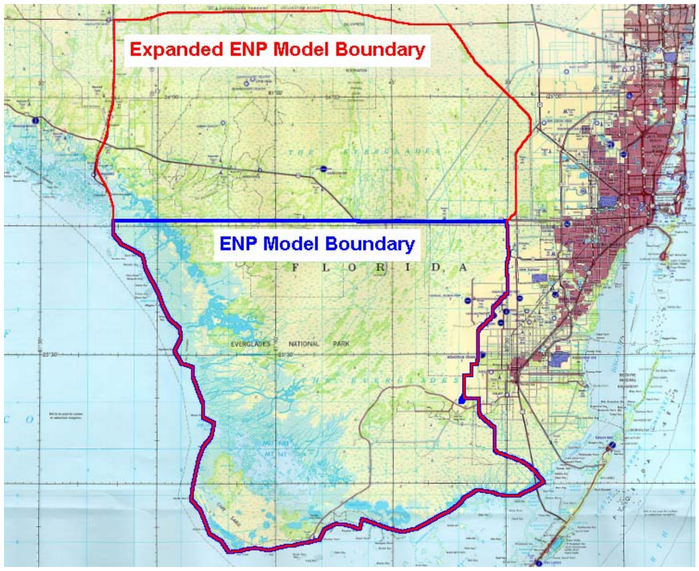

Figure 7. Expanded ENP Model Extents.

As a final step in the expansion process, two 3-D finite element meshes were generated for this impact assessment study. The first mesh contains the canals, control structures and levees as they existed at the time that the input boundary condition data were collected. After calibration of the first mesh using existing conditions, the mesh was altered to incorporate the changes to canals, levees and control structures dictated by the CERP scenarios. The second mesh was then run using the results of the first mesh calibration as an initial condition. In this fashion, "base-to-plan" comparisons can be easily made and the impacts of the proposed changes assessed. Figures 8 and 9 depict surface water depth contours on both the "base" and "plan" meshes. Note the differences in water depths in the eastern portions of the study area and the larger extent of inundated land due to the plan changes.

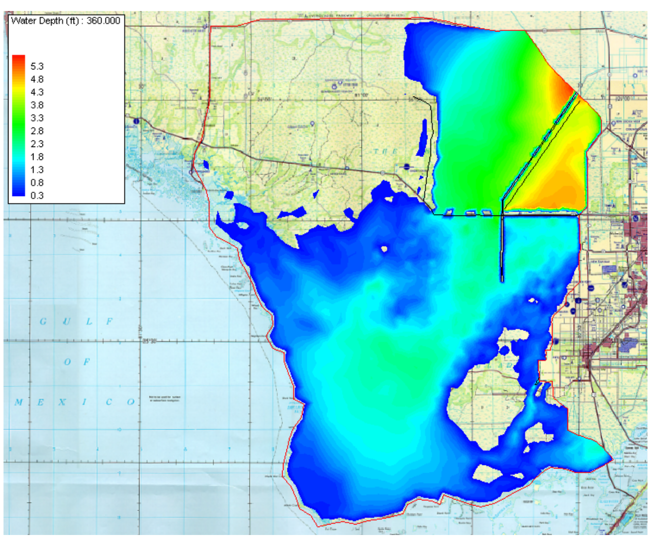

Figure 8. Expanded ENP Model Base Condition Water Depth Contours.

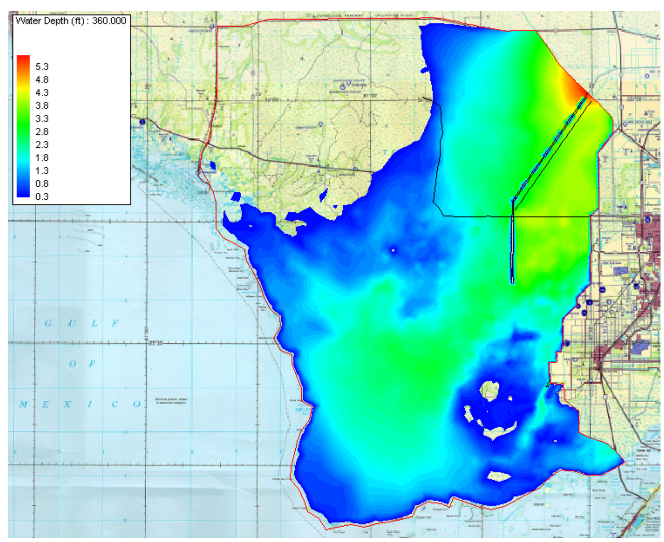

Figure 9. Expanded ENP Model Plan Condition Water Depth Contours

Tools for Assessment. Tools are provided within GMS for building conceptual models, generating FEMWATER123 model simulations and for evaluating model simulation results. Using the tools found in GMS and FEMWATER123, the entire model expansion and assessment described above was completed in less than one man-week. More complex changes or additions might require more time. However, there is considerable value in being able to quickly and accurately make predictions of impacts due to proposed changes in the South Florida system using the tools described.

Conclusions

Working with and proposing changes to the South Florida hydrologic system is highly complex for both technical and political reasons. Hydroinformatic systems are needed that can both accurately simulate the many physical processes and provide sophisticated tools to decision makers – all of which must be carried out in a timely fashion. A coupled multidimensional numerical modeling code is required in order to simulate the complex conditions found in South Florida with the required degree of accuracy. The combination of capabilities and tools in FEMWATER123 and GMS meet the needs of such a hydroinformatic system. Application of this hydroinformatic system to the current conditions in South Florida has demonstrated its ability to simulate the response of the system to recorded hydrologic events. Impacts of proposed changes to the South Florida hydrologic system can also be quickly and accurately simulated using this hydroinformatic system.

Acknowledgements

Permission was granted by the Chief of Engineers to publish this information.

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