MODEL CALIBRATION AND VALIDATION OF SOUTH FLORIDA BISCAYNE BAY COASTAL WETLANDS WATERSHED

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ABSTRACT

Among the projects in the Florida Comprehensive Everglade Restoration Plan (CERP), the Biscayne Bay Coastal Wetlands (BBCW) project has a purpose of re-hydrating wetlands and reducing point source discharge to Biscayne Bay. Seven project alternatives that include rule-controlled coastal canal structures, rule-controlled pump stations, spreader swales, stormwater treatment areas, flowways, levees, culverts, roads, and backfilling canals have been proposed to achieve the purpose. These alternatives are evaluated with the WASH123D model: a first-principle, physics-based numerical model that computes flow and transport in a watershed system that is conceptualized as a combination of 1-D channel network, 2-D overland regimes, and 3-D subsurface media. The WASH123D-BBCW model needs to be calibrated and validated before being used to evaluate the alternatives. This paper presents the calibration and validation of the model. A three-step approach that is used for model calibration and validation is presented, discussed, and evaluated in this paper. The three steps are: calibration of the overland Manning's roughness coefficients (n2) and subsurface hydraulic conductivities (K) with the coupled 2-D/3-D WASH123D-BBCW model where the historical data of canal stage is used as the boundary condition; calibration of the canal Manning's roughness coefficients (n1) where the calibrated n2 and K from the previous step are used; and validation of the calibrated n1, n2, and K with a second set of historical data. The calibration-validation results of the WASH123D-BBCW model are also presented in the paper.

1. INTRODUCTION

The BBCW project is a CERP project that has a mission of constructing pump stations, spreader swales, stormwater treatment areas, flowways, levees, culverts, and backfilling canals in order to restore the overland sheet flow and subsequently improve the ecology of Biscayne Bay (http://www.evergladesplan.org/pm/projects/proj_28_biscayne_bay.cfm). To simulate water movement in the BBCW project domain for project alternative evaluation, key hydrologic processes such as infiltration/seepage, canal flow, and relatively fast groundwater flow must be adequately resolved and incorporated into the computational engine selected.

The WASH123D numerical model (Yeh et al., 2006) was chosen to help evaluate various alternatives for the project purposes because it is a first-principle, physics-based finite element model that allows different time step sizes used for 1-D canal flow, 2-D overland flow, and 3-D variably saturated subsurface flow computation as needed and thus is capable of resolving the key hydrologic processes mentioned above. This paper briefly states the model calibration and validation efforts and results for the WASH123D-BBCW model.

2. MODEL CALIBRATION AND VALIDATION APPROACH

2.1 Model Parameters to calibrate

The WASH123D numerical model served as the computational kernel of the WASH123D-BBCW model, where the cross section-averaged 1-D diffusive wave equation, the depth-averaged 2-D diffusive wave equation, and the 3-D Richards equation were solved with semi-Lagrangian and Galerkin finite element methods for canal network flow, overland flow, and variably-saturated subsurface flow, respectively (Yeh et al., 2006). With WASH123D, a watershed system is conceptualized as a combination of 1-D canal networks, 2-D overland regimes, and 3-D subsurface media. The physical model parameters to be calibrated and validated are the Manning's roughness coefficients for 1-D canal flow (i.e., n1), the Manning's roughness coefficients for 2-D overland flow (i.e., n2), and saturated hydraulic conductivities for 3-D subsurface flow (i.e., K) given fixed soil curves.

2.2 Model conceptualization

In WASH123D where the computational domain is discretized with finite element meshes, each element can be assigned with a different material type to account for heterogeneity, and each material may have its own set of physical model parameters. However, due to the availability of applicable field data and the limited time for model calibration and validation, the following conceptualization was adopted in the WASH123D-BBCW model.

(1) One Manning's roughness coefficient was used for each canal reach, where the ends of a canal reach may be a upstream boundary, a downstream boundary, a dead end, a canal junction, the headwater (HW) of a canal structure, or the tail water (TW) of a canal structure.

(2) One Manning's roughness was applied to each overland material, where the WASH123D-BBCW overland computational domain was composed of four materials, namely Urban, Croplands, Rangelands, and Wetlands.

(3) One set of saturated hydraulic conductivities, including horizontal and vertical conductivities, were considered for each subsurface material identified in the computational domain, where seven materials were included. They are four types of top soil that are associated with the four overland materials, one canal bottom material, Miami Oolite, and Ft. Thompson Formation. The following soil curves were adopted for all these seven materials due to their simplicity.

(Eq. 1) $$MC = 0.11 + WC * (h + 15)$$

(Eq. 2) $$RC = 0.1 + 0.06 * (h + 15)$$

where MC is moisture content (L^3/L^3), WC is water capacity (L^3/L^3L), h is pressure head (L), and RC is relative conductivity (dimensionless). Here the length unit is foot.

2.3 Calibration and validation periods

Since the water flow in South Florida is basically rainfall driven, the three water years used for model calibration and validation were selected based on the yearly rainfall and the completeness of rainfall data, where the wet year (May 1995-April 1996) and the dry year (May 1999-April 2000) were selected to represent two extreme system conditions during the past decade for model calibration, and the average year (May 1998-April 1999) was used for model validation. The computational results were compared against the observed data for the corresponding years to evaluate the ability of the fully coupled 1-D/2-D/3-D model to reproduce historical results.

2.4 Error measures

To determine adequate sets of model parameters, mean absolute error (*MAE*) and the root mean squared error (*RMSE*) were used as error measures for model calibration and validation. They are defined as follows:

(Eq. 3)
$$MAE = \frac{\sum_{i=1}^{n} \left| Computed_i - Observed_i) \right|}{n}$$

(Eq. 4)
$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left| Computed_i - Observed_i) \right|^2}{n}}$$

where n is the number of comparisons between the computed and observed values.

2.5 A three-step approach for model calibration and validation

Due to the complexity of the WASH123D-BBCW model as well as a very tight project schedule, a three-step approach has been developed and implemented for model calibration and validation. The three steps are as follows.

Step 1. Calibrate the coupled 2-D overland and 3-D subsurface flow parameters (i.e., n2 and K) while applying historical measurements of 1-D canal stages as boundary conditions by adjusting parameter values to match historical measurements of groundwater head and overland water stage for all the three water years selected.

Step 2. Calibrate the 1-D canal flow parameters (i.e., n1) in the coupled 1-D/2-D/3-D model with fixed n2 and K that are obtained from Step 1 for the wet year (i.e., 1995-1996) and dry year (i.e., 1999-2000), where the computed and observed HW and TW stages of canal structures are compared.

Step 3. Validate the coupled 1-D/2-D/3-D flow model by comparing model results to historical measurements of groundwater heads and overland and canal water stages for the average year (i.e., 1998-1999) by using the flow parameters obtained from Steps 1 and 2.

2.6 Computational domains

Figure 1 depicts the boundaries of the coupled 2-D/3-D model (in blue) and the coupled 1-D/2-D/3-D model (in red). The coupled 2-D/3-D model used in Step 1 had the C-3 and the C-4 canals as the northern boundary, the L-31N and the C-111 canals as the western boundary, and the eastern and southern boundaries selected based on the available observed canal stage or groundwater head. Figure 2 shows the 2-D and 3-D meshes of the coupled 2-D/3-D model that was generated by GMS (http://chl.erdc.usace.army.mil/gms) and contains 8,339 nodes and 16,388 triangular elements in 2-D discretization and 66,712 nodes and 114,716 triangular prism elements in 3-D discretization. The observed groundwater head from 24 wells (Figure 3) were used as the calibration targets.

The computational domain of the coupled 1-D/2-D/3-D flow model is about 1/3 the area of the coupled 2-D/3-D model. It is small enough that one-year simulations could be completed in twelve days on single alpha processor machines, while still large enough to allow an evaluation of the selected BBCW alternatives. The subsurface flow results (i.e., total heads) from the coupled 2-D/3-D flow model were used to determine the western boundary condition on the western boundary of the coupled 1-D/2-D/3-D model (Figure 4).

2.7 Simulation set-up

The upstream canal boundary condition was the hourly TW stages (computed from the 15-minute observed historical data) of the coastal ridge canal hydraulic structures (i.e., S-120, S-119, etc., Figure 3). The downstream canal boundary condition was the hourly TW stages (computed from the 15-minute observed historical data) of the coastal canal structures: Coastal Structure S-123 for the C-100 canal, Coastal Structure S-21 for the C-1 canal, Coastal Structure S-21A for the C-102 canal, Coastal Structure S-20G for the Military Canal, and Coastal Structure S-20F for the C-103 canal (Figure 3). At each coastal structure, the flow is computed based on the computed HW stage, the given TW stage, the structure characteristics (e.g., width, height, type, and etc.), and the gate opening as specified by a set of operating rules as detailed later in this document.

The overland flow stages from the coupled 2-D/3-D flow model were used to determine the western boundary overland flow condition via interpolation. The eastern, downstream, overland boundary north of coastal structure S-21 was a rating curve based on the topographic data. For the boundary south of S-21 a zero-depth boundary condition was set at all the overland boundary nodes corresponding to the L-31 canal levee and road, making these structures surface water divides.

To start each simulation with a reasonable and stable initial condition, the initial canal stages were first calculated through an interpolation process based on the hourly HW and TW stage information from the 15-minute observed historical data. The calculated initial canal stages were then applied at the canal-corresponding subsurface nodes as boundary conditions to compute steady-state subsurface flow, which ensures the continuity of state variables (i.e., canal stage equals groundwater head) on the canal-subsurface interface. The steady-state subsurface flow solutions were then used as the initial condition for the subsequent transient simulations. Based on rainfall, ET, initial canal stage, and initial subsurface total head along the domain boundary the entire overland domain was assumed initially dry for all model runs. This assumption was validated by the pressure head solution of the steady state flow computation, i.e., all the overland corresponding subsurface nodes had negative pressure heads, representing a dry ground surface.

In all WASH123D-BBCW simulations, the computational time interval was 0.5 hours for 3-D subsurface, 5 seconds for 2-D overland, and 0.5 seconds for 1-D canal flow. The absolute error in head is used in WASH123D to determine nonlinear convergence. The convergence criteria were set to 10^{-4} ft, 10^{-5} ft and 10^{-5} ft for 3-D, 2-D, and 1-D computations, respectively.

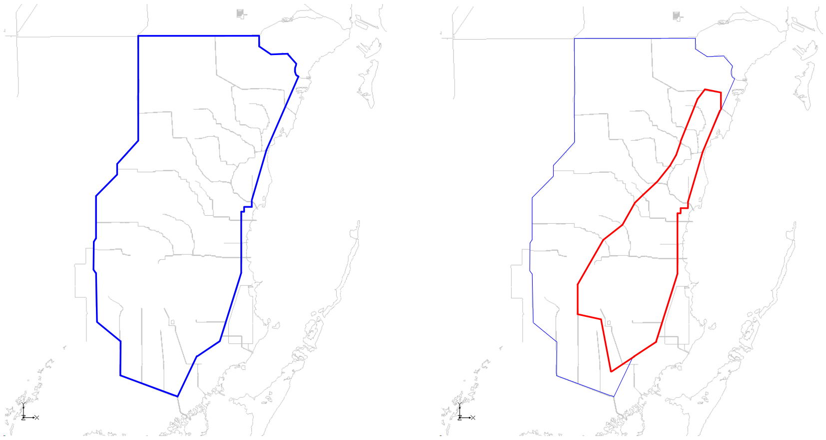

FIGURE 1. The boundaries of the coupled 2-D/3-D model (left) and the coupled 1-D/2-D/3-D model (right, highlighted in red).

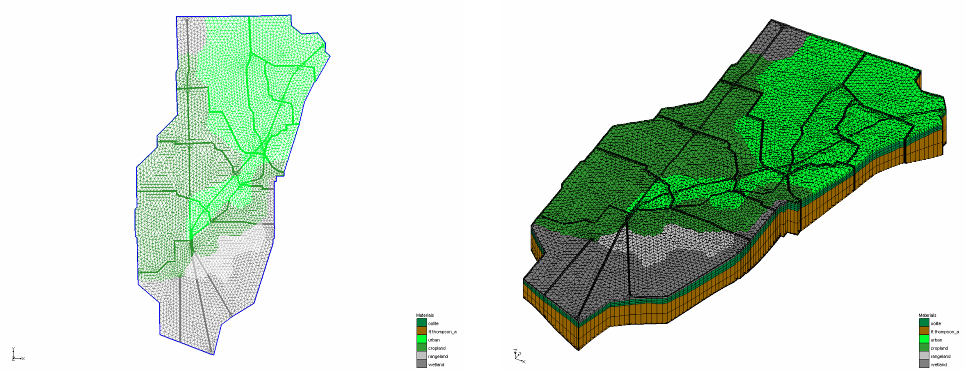

FIGURE 2. The computational mesh of the coupled 2-D/3-D model: 2-D (left), 3-D (right).

3. RESULTS

The regular WASH123D-BBCW solution files include (1) water stage and flow rate at all 1-D canal nodes, (2) water stage and flow velocity at all 2-D overland nodes, and (3) pressure head, flow velocity, and moisture content at all 3-D subsurface nodes. These temporally varying values are output at desired frequencies. In all the simulation runs for model calibration and validation, the 3-D subsurface flow solution was output every 6 hours while the 1-D canal flow and 2-D overland flow solutions were output hourly. In the following the 15-minute data represents the information directly obtained or derived from the observed historical field data (e.g., gate opening and HW and TW stages were the observed data while structure flow rate was calculated by substituting gate open, HW and TW stages into the associated calibrated equations).

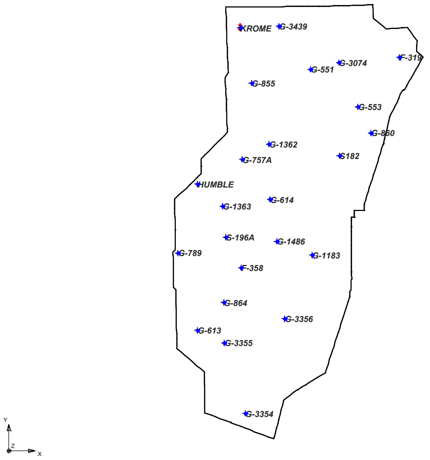

FIGURE 3. The BBCW groundwater observation wells in the coupled 2-D/3-D flow model domain for model calibration and validation.

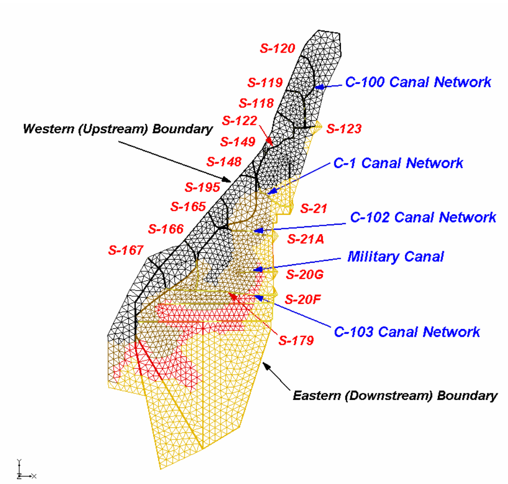

FIGURE 4. WASH123D-BBCW computational domain for the coupled 1-D/2-D/3-D model.

3.1 Coupled 2-D/3-D model (Step 1)

Figure 4 shows the locations of the groundwater observation wells for coupled 2-D/3-D flow model calibration. Table 1 shows the calibrated n2 and K from a total of 41 coupled 2-D/3-D simulation runs based on the overall *MAE* and *RMSE* (not shown here).

3.2 Coupled 1-D/2-D/3-D model (Steps 2 & 3)

By fixing the n2 and K values obtained from Step 1 (Table 1) and, 7 simulations of coupled 1-D/2-D/3-D flow were conducted where the starting n1 values were adopted from the literature (Chow, 1959) and those used in MODBRNCH (http://water.usgs.gov/cgi-bin/man_wrdapp?modbrnch). The calibrated n1 values are 0.035 for C-1, Military, and C-103 canal networks, and 0.05 for C-100 and C-102 canal networks.

Figures 5 plots the comparison of stages of S-123 HW between the computed and the 15-minute data for all the three years. Table 2 lists the error measures of canal water stage at six locations for the wet, the dry, and the average years, respectively. The averaged hourly *MAE*s are 0.24 ft, 0.14 ft, and 0.17 ft for the wet, the dry, and the average years, respectively. The averaged hourly *RMSE*s are 0.33 ft, 0.20 ft, and 0.27 ft for the dry, the wet, and the average years, respectively. It is noted from Table 2 that the MAEs and RMSEs for the wet year are consistently greater than the respective ones in the other years, except for S-179 TW. More investigations are needed to identify the reasons and to further refine the model.

TABLE 1. Calibrated n2 and K from the coupled 2-D/3-D model.

Material Type	n2 (dimensionless)	$K_{horizontal}/K_{vertical}$ (ft/hr)
Urban	0.1	NA (Not Applicable)
Croplands	0.15	NA
Rangelands	0.1	NA
Wetlands	0.05	NA
Top soils	NA	0.1/0.01
Canal Bottom	NA	250/25
Miami Oolite	NA	1000/100
Ft. Thompson	NA	800/80

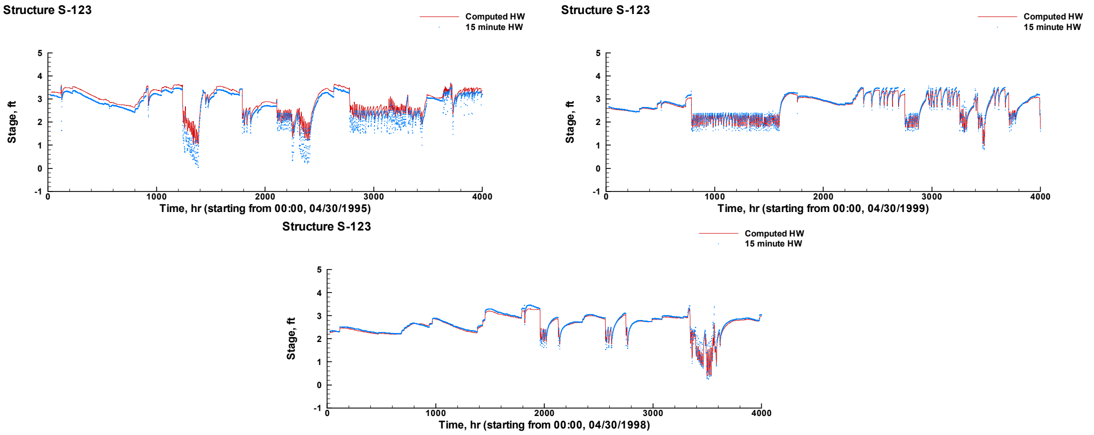

FIGURE 5. Comparison of HW stage at S-123 from the computed and the observed (the 15-minute data) for the three years of model calibration and validation.

TABLE 2. Error measures of canal stages.

Canal Water Stage	Wet Year (1995-1996)		Dry Year (1999-2000)		Average Year (1998-1998)	
	MAE (ft)	*RMSE* (ft)	*MAE* (ft)	*RMSE* (ft)	*MAE* (ft)	*RMSE* (ft)
S-123 HW	0.24	0.31	0.06	0.08	0.06	0.09
S-21 HW	0.30	0.50	0.17	0.30	0.22	0.38
S-21A HW	0.40	0.51	0.15	0.26	0.25	0.36
S-20F HW	0.18	0.23	0.16	0.20	0.15	0.22
S-179 HW	0.06	0.10	0.04	0.08	0.07	0.20
S-179 TW	0.21	0.27	0.21	0.26	0.23	0.36

Figure 6 plots the comparison of GW head between the computed and the observed at G-860 for the three years. Table 3 gives the error measures of GW head at the three observation wells included in the coupled 1-D/2-D/3-D model. The averaged daily *MAE*s are 0.22 ft, 0.18 ft, and 0.18 ft for the wet, the dry, and the average years, respectively, while the averaged daily *RMSE*s are 0.30 ft, 0.23 ft, and 0.25 ft for the three respective years.

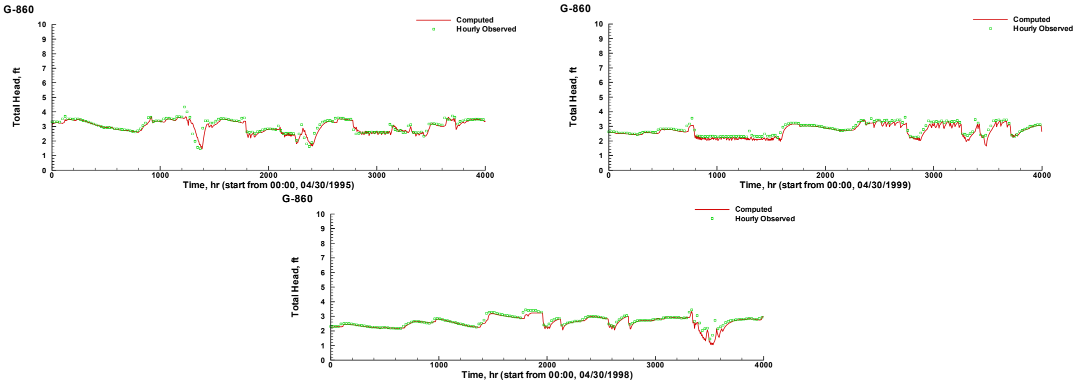

FIGURE 6. Comparison of groundwater total head at G-860 from the computed and the daily observed for the three years of model calibration and validation.

TABLE 3. Error measures of groundwater total heads.

GW Observation Well	Wet Year (1995-1996)		Dry Year (1999-2000)		Average Year (1998-1998)	
	MAE (ft)	*RMSE* (ft)	*MAE* (ft)	*RMSE* (ft)	*MAE* (ft)	*RMSE* (ft)
G-860	0.11	0.19	0.15	0.21	0.10	0.18
G-1486	0.24	0.28	0.16	0.22	0.20	0.24
G-1183	0.31	0.41	0.21	0.26	0.25	0.32

SUMMARY

The paper presented the calibration and validation of the WASH123D-BBCW model. Three water years (wet: 1995-1996; dry: 1999-2000; average: 1998-1999) were selected as the simulation periods. A three-step strategy was developed for this work: calibrate n2 and K in the coupled 2-D/3-D model with canal stages applied on the model as boundary conditions (Step 1), calibrate n1 in a coupled 1-D/2-D/3-D model with n2 and K fixed (Step 2), and validated the coupled 1-D/2-D/3-D model with the dry year data. Without overland stage data provided, 24 groundwater heads were employed for the calibration of the coupled 2-D/3-D model, where the large mesh was used. Figures 5, 6 and Tables 1 through 3 show partial calibration and validation results. It is believed that the WASH123D-BBCW model was calibrated and validated based on the system data provided and adequate for project alternative evaluation.

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