NUMERICAL STRATEGIES TO MODEL HYDROLOGIC FEATURES FOR THE BISCAYNE BAY COASTAL WETLANDS PROJECT ALTERNATIVES

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ABSTRACT

WASH123D is a first-principle, physics-based numerical model that computes flow and transport in a watershed system that can be conceptualized as a combination of 1-D channel networks, 2-D overland regimes, and 3-D subsurface media. It has been selected as the tool to help evaluate the proposed alternatives of the Biscayne Bay Coastal Wetlands project that is one of the projects included in the Florida Comprehensive Everglade Restoration Plan. In order to best re-hydrate wetlands and reduce point source discharge to Biscayne Bay, rule-controlled coastal canal structures, rule-controlled pump stations, spreader swales, stormwater treatment areas, flowways, levees, culverts, roads, and backfilling canals are included in these project alternatives. Specified target freshwater flows for Biscayne Bay and the wetlands within the redistribution system are to be computed in each alternative, which will be used in performance measurement to determine the most adequate alternative for further investigation. In this paper, numerical strategies to incorporate into WASH123D all the aforementioned hydrological features and processes included in the alternatives are presented. An example alternative will be used for demonstration.

1. INTRODUCTION

With a mission to construct 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, a tentative selected plan is determined based on the comparison of the performance measure scores of the seven project alternatives proposed in the South Florida Biscayne Bay Coastal Wetlands (BBCW) project (http://www.evergladesplan.org/pm/projects/proj_28_biscayne_bay.cfm). The BBCW project is one of the Comprehensive Everglades Restoration Plan (CERP) projects that have an overall goal to restore and preserve the Florida Everglades (http://www.evergladesplan.org/). After the selected numerical model, WASH123D (Yeh et al., 2006), was calibrated and validated with the historical field data (Cheng et al., 2006a), the model parameters associated with the validated model are fixed in the simulation runs for project alternative evaluation. Each alternative may differ from others in the features included, the structure operation rules adopted, and the boundary conditions applied. The focus of this paper is to address how the hydrologic features employed in the seven project alternatives were numerically resolved in WASH123D.

2. HYDROLOGIC FEATURES IN BBCW PROJECT ALTERNATIVES

The key hydrologic processes in the BBCW model domain include infiltration/seepage, canal flow, and relatively fast groundwater flow. To adequately resolve these processes, a numerical strategy that couples surface and subsurface water flow systems has been developed and incorporated into WASH123D, where different time step sizes can be used for computations in different dimensions (Cheng et al., 2004). For instance, in all the WASH123D-BBCW simulation runs, the time step sizes were 30 minutes for 3-D subsurface flow, 5 seconds for 2-D overland flow, and 0.5 second for 1-D canal flow. To better manage water distribution for a healthier coastal wetlands ecologic system, various features were employed into the seven BBCW project alternatives. They are briefly described as follows.

2.1 Rule-controlled canal structures

There are five coastal canal structures (i.e., S-123, S-21, S-21A, S-20G, and S-20F) and two interior canal structures (i.e., S-122 and S-179) in the coupled 1-D/2-D/3-D WASH123D-BBCW model (Figure 1), where S-122 stayed closed as operated. The automatic operations considered at the other six canal structures include the following.

(1) Salinity Regulation:
The structure gates should stay closed or start to close if the headwater (HW) stage is not higher than the tail water (TW) stage by a desired differential (e.g., 0.3 ft).

(2) Trigger Rules:
If the HW stage is higher than the open trigger, the structure gates open at a speed of 0.5 ft/min; if the HW stage is lower than the close trigger, the structure gates close at a speed of 0.5 ft/min; if the HW stage is between the open and the close triggers, the structure gate openings are unchanged.

(3) Manatee Protection Operation:
When the structure gates are to open from the fully closed position, they will open all the way to a 2.5 ft opening; and if they are to close from the 2.5 ft opening, they close all the way to a fully closed position at the 0.5 ft/min rate, i.e. a minimum gate opening of 2.5 ft is used.

(4) Opening and Closing Rules:
After reaching the 2.5 ft opening, the HW stage is compared with the open and close triggers for operation action every 0.5 ft. In other words, the checkpoints are set at 2.5 ft, 3 ft, 3.5 ft, etc., up to the allowed maximum gate opening.

(5) Multiple-Gate Rules:
If a canal structure has more than one gate, the second gate (i.e., gate #2) is the primary discharge structure and will open from zero to 2.5 ft prior to the others; then if greater discharge capacity is needed, gate #2 stays at 2.5 ft while the others open to 2.5 ft; after all gates reach the 2.5 ft open position, all the gates open and close together until reaching the 2.5 ft open position; gate #2 will close from 2.5 ft down to zero after the other gates are fully closed.

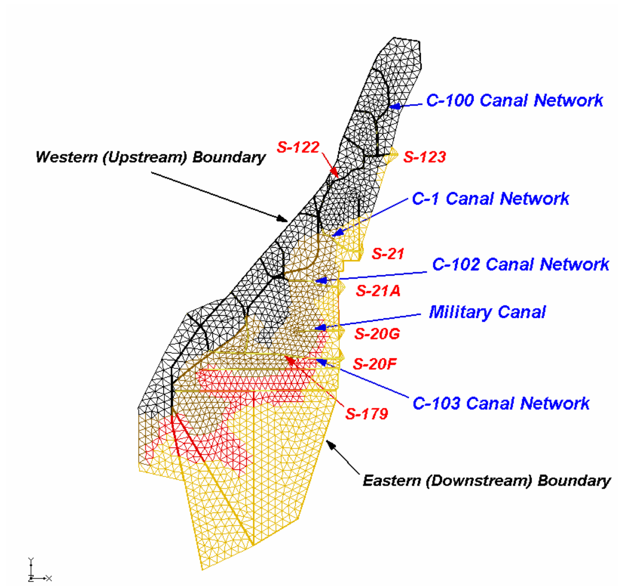

FIGURE 1. WASH123D-BBCW computational mesh for Existing Condition.

2.2 Stormwater treatment areas (STAs) & flowways

STAs are used to treat agricultural and urban runoff before it flows into the Everglades, so that excess phosphorus in stormwater runoff from agricultural, residential, and urban areas can be absorbed efficiently by certain types of vegetation planted in them before reaching the Everglades (http://www.sfwmd.gov/images/pdfs/splash/sta.pdf). As a result, the risk to harm the marsh ecosystem is greatly reduced. Flowways serve similar purposes.

2.3 Storage reservoirs

Storage reservoirs are used to capture, store and redistribute freshwater previously lost to tide and to regulate the quantity, timing, and distribution of water for environmental deliveries. (http://www.evergladesplan.org/pm/projects/proj_08_eaa_phase_1.cfm)

2.4 Spreader swales

Spreader swales are used to redistribute available surface water entering the area from the regional canal system. The spreader swale system could consist of a delivery canal and shallow swales where water flows across the swale banks and becomes a more natural overland flow through existing coastal wetlands (Cheng et al., 2004).

2.5 Rule-controlled pump stations

The rule-controlled pump stations are used to move water from source locations to target locations according to the corresponding operation rules. Water can be pumped among canal, overland, and subsurface systems for desired purposes. The triggers employed to activate or deactivate pumping can be surface water stages/depths or groundwater heads.

2.6 Levees

Levees are used to separate surface waters. They can be water divides between canal water and overland water, STA/reservoir water and overland water, and canal water and

STA/reservoir water. Depending on the material used to construct levees, they can vary from highly permeable to impermeable.

2.7 Culverts

Culverts, in most cases, are conveyance channels to allow surface water to flow from one side of water divide to the other. Depending on the design, water flow through culverts may go in one or both directions.

2.8 Major roads

Major roads can be considered to be equivalent to levees that are used to separate surface waters on the two sides.

2.9 Backfilled canals

If a canal is backfilled and its levees are removed, there will be no surface water divides along the canal any more. However, if the levees still exist, the backfilled canal and its levees combined will serve as overland water divide.

3. NUMERICAL STRATEGIES

WASH123D is designed to be a first-principle, physics-based numerical model, where hydraulic gradients calculated based on the surface water stages and groundwater heads determine the directions of surface flow and subsurface flow, respectively (Yeh et al., 2006). To model the aforementioned hydrologic features adequately, the following numerical strategies have been employed.

3.1 Sufficient spatial and temporal resolutions

To resolve the physical processes associated with the hydrologic features mentioned above in WASH123D, not only the physics must be represented correctly but the spatial and temporal resolutions for simulation runs must be sufficient also. For instance, both levees and major roads are presented with elevated ground in the computational mesh to represent surface water divides (Figure 2), and the maximum 1-D flow time step size cannot be greater than 30 seconds so that the “Opening and Closing Rules” for canal structure operation (see in Section **2.1** above) would be adequately resolved. After a number of simulation runs for sensitivity analysis and numerical stability test, the average horizontal spatial interval for the BBCW model was between 1,000 and 1,500 ft, the average thickness of the top two subsurface elements were 2 ft, the time step sizes were 30 minutes, 5 seconds, and 0.5 seconds for 3-D, 2-D, and 1-D computations. The average widths of major roads and levees were assumed 100 ft and 50 ft, respectively.

3.2 Zero-dimensional flow features

Both reservoirs and STAs (or flowways) are simulated with zero-dimensional (0-D) ponds in WASH123D, where water budget is calculated to determine the water stage. Included in water budget calculation are infiltration/seepage, rainfall, evapotranspiration, and other sources/sinks. These 0-D ponds have elevated levees that serve the same purpose as canal levees (Figure 2). The main difference between reservoirs and STAs is in the materials used to define the boundary. Usually, impermeable materials are used for reservoirs so that only limited amount of water will infiltrate into the subsurface, while the bottom material for STAs are usually more permeable, while allows interaction between STA water and groundwater through infiltration and seepage.

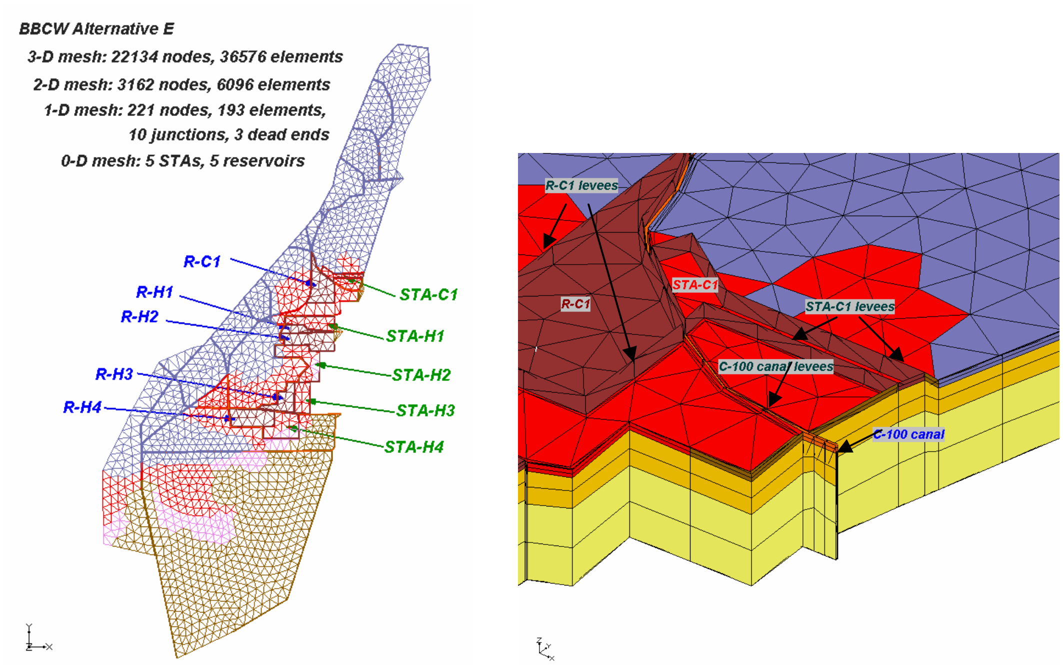

FIGURE 2. WASH123D-BBCW computational mesh for Alternative E: levees are represented with raised elevation to serve as surface water divides (right).

3.3 Rule-controlled pumping

Pumping is treated as either a source term or a sink term, depending on whether it is an injection or withdrawal. When pumping is controlled by specific rules, a rating curve (Eq. 1) that incorporates the pumping operation rules will be used to determine the pumping rate.

(Eq. 1) $$Q_{pump} = f(time, operation\_rules)$$

In WASH123D, each rule-controlled pumping is specified by the corresponding operation rule that includes the information of designated pumping rates, operation triggers, source and target locations, and the actual pumping rate is computed in the subroutine that contains all the operation rule data.

To allow water pumped across dimensions at desired times as the operation describes, a computation algorithm to account for inter-dimensional pumping has been developed and implemented in WASH123D as depicted in Figure 3. In Figure 3, Sites 1 and 2 represent the source and target locations, respectively. The subroutine to compute the actual pumping rate for a pump is called at a frequency as determined by the corresponding operation rule. If ILVLPMP(IP) = 2, for instance, the pumping subroutine is called to update the actual pumping rate in every 2-D time step. Since the source and the target locations may be in different dimensions, pumping rate bookkeeping (highlighted in blue in Figure 3) for each rule-controlled pump is essential. The implementation of inter-dimensional pumping enables WASH123D to simulate any feature that can be modelled by rule-controlled sources and sinks, including pump stations, culvert flows, spreader swales, injection and withdrawal in reservoirs and STAs.

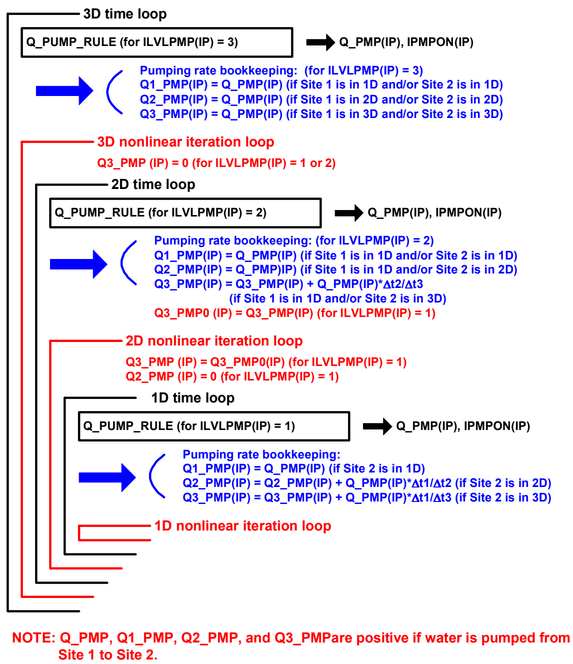

FIGURE 3. Inter-dimensional pumping in WASH123D for a coupled 1D canal network, 2D overland, and 3D subsurface watershed system

3.3 Rule-controlled canal structures

The rate of flow passing across a canal structure may be controlled by the HW stage, the TW stage, and structure characteristics (*e.g.*, gate type, gate opening, control rules, etc.), and the flow rate can be considered a function of these factors (Eq. 2), known as a rating curve.

(Eq. 2) $$Q_{control\ \ structure} = f(HW, TW, structure\_characteristics)$$

Each canal structure may have a rating curve or even a set of rating curves that are different from those used for the other structures. Therefore, with all the rating curves identified and incorporated into the computer code for the desired structures, the flow rate at each structure can be computed, which serves as the downstream boundary condition for its upstream reach and the upstream boundary condition for its downstream reach. That way, the continuity of flux across the canal structure is maintained.

4. DEMONSTRATION EXAMPLE

Due to the limit of paper length, an example showing only the implementation of canal structure operation rules is provided below. The computational results at Canal Structure S-123 from the wet year (i.e., 1995-1996) simulation run were analyzed in order to verify the implementation of the published operation rules of canal structures as defined in Table 1. Figure 4 shows the computed gate openings and the computed outflow (top), as well as the comparison between the computed and the observed HW stages at Structure S-123 (bottom), where the programmed open trigger and close trigger values, as specified in Table 1, are also provided as a reference to examine whether or not the trigger rules have been correctly implemented in the model.

TABLE 1. Rules controlling gate opening and closing at S-123.

Coastal Structure	Rules
S-123 (C-100)	* Manatee Protection Operation: Fully close ←→ 2.5 ft
Gate No. = 2	* Opening and Closing Rules: Check points at 2.5, 3, 3.5, … ft
Gate width = 25 ft (each)	* Salinity Regulation: HW-TW > 0.3 ft
Max. gate opening = 15.7 ft	* Trigger Rule (Dry Condition Operations):
$Q\_S123 = C_d LG\sqrt{2g(HW-TW)}$	HW ≥ 3.5 ft-open at 0.5 ft/min
Qout = Q_S123 (Output to TABS)	HW ≤ 2.5 ft-close at 0.5 ft/min

To illustrate the complexity of the programmed operating rules, the operations for S-123 are described in detail below, with emphasis on the gate open and close triggers. More detailed description can be found elsewhere (Cheng et al., 2006b)

- As illustrated in Figure 4, S-123 gate #2 opens to 2.5 ft at around Time = 120 hrs when the computed HW stage hits the open trigger (i.e., 3.5 ft).
- The computed HW stage stays between the open trigger and the close trigger (i.e., 2.5 ft) up to Time = 1,162 hrs until the HW stage hits the open trigger again, which results in the opening of the other gate (i.e., gate #1) increasing the computed outflow.
- Both gates remain open between Time = 1,162 and 1,245 hrs when the computed HW stage is between the open and close triggers. At Time = 1,245 hrs, the computed HW stage hits the close trigger, and gate #1 closes first.
- Between Time = 1,245 and 1,254 hours, the computed HW stage stays above the close trigger, which keeps gate #2 open during this period. At Time = 1,254, gate #2 closes because the close trigger is hit again. After that both gates remain closed for 291 hours.
- When the computed HW stage hits the open trigger again at Time = 1,545 hrs, gate #2 re-opens. While gate #2 remains open at 2.5 ft, gate #1 remains closed because the open trigger is not hit again.
- The third time the gates open is at Time = 2,631 hr. Although gate #2 opens before gate #1 according the multiple-gate rules, it is not distinguishable in Figure 4 because the computed gate opening is stored in the solution files every 30 minutes, and during a 30 minute time period both gates may be opened if the computed HW stage is higher than the open trigger when gate #2 opens to 2.5 ft, as it takes only 5 minutes for a gate to open from zero to 2.5 ft.
- At Time = 2,642 hrs the next open trigger is reached and both gates open further to 3.0 ft. Both gates are held open at 3.0 ft between Time = 2,642 and 2,780 hrs because the computed HW stage stays between the open and the close triggers. The gate opening is reduced from 3.0 ft to 2.5 ft when the close trigger is reached at Time = 2,780 hrs.
- When the next close trigger is reach one hour later, gate #1 closes first. Gate #2 starts to close at Time = 2,783 hrs when the next close trigger is reached and #1 gate is fully closed. Gate #2 re-opens to 2.5 ft at around Time = 3,639 hrs. Gate #1 remains closed until Time = 3,707 hrs. Both gates open further to 3.0 ft at Time = 3,708 hrs then start to close when the computed HW stage reaches the close trigger at Time = 3,727 hrs. Similar processes repeat between Time = 3,859 and 4,112 hrs.

- The last gate opening-closing activity occurs between 4,232 and 4,237 hrs. After that both S-123 gates remain closed because the computed HW stage never reaches the first open trigger.

Similar analysis can be conducted for all the gate opening-closing processes at the other structures. This analysis verifies the correctness of implementing the documented automated structure rules as listed in Table 1 in the WASH123D-BBCW model.

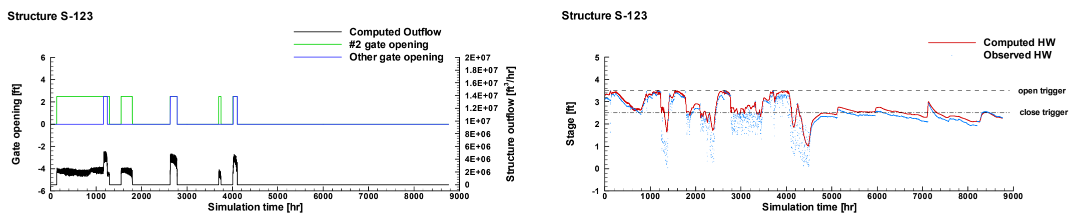

FIGURE 4. WASH123D computational results to verify the implementation of canal structure operation rules.

5. SUMMARY

This paper described the numerical strategies employed in the WASH123D-BBCW model to account for various features included in the seven BBCW project alternatives in order to help determine a tentative select plan. Sufficient spatial and temporal resolutions for numerical simulation, 0-D ponds, and rule-controlled pumping and canal structures are key to successfully model the alternative features. An inter-dimensional pumping algorithm and an example to verify the implementation of the canal structure rules were given.

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