Progress Report

Development of a Hydrodynamic and Water Quality Model for the Coral Gables Canal and the Biscayne Bay (Florida, USA)

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Executive summary

This document is a progress report on the development of a water quality model for the Coral Gables Canal and the Biscayne Bay (Florida, USA). Details are presented on the study area, initial modeling efforts, input data used for developing the modeling tools, calibration and validation of the models, scenarios of water quality exploration, and future steps to improve the model. Hydrodynamic calibration and validation results indicate that the model correctly simulates water transport, especially for the northern sectors of the bay ($R^2 > 0.93$, NSE > 0.83, RSR < 0.41, K-G > 0.23). Estimations of the hydrodynamic regime for southern Biscayne Bay can be improved although only the statistical indicator of bias is not adequate. Water quality scenarios simulations show that the model correctly captures the spatial distribution of water quality constituents' concentrations. Nevertheless, the concentration values for all water quality constituents simulated by the model must be improved. This will be achieved when an existing watershed model is implemented for calculation of more realistic inputs of flow and contaminant concentrations to the canal and the bay.

1. Introduction

Biscayne Bay is a coastal water body located in southeast Florida. The area surrounding the bay, which originally was dedicated to agriculture, has experienced rapid urban growth in the last decades. The combined effects of human activities (urban settlements and agriculture) have increased nutrient runoff from inland to the bay. Recent studies have identified increased chlorophyll-a and phosphate concentrations within the bay, which is more evident throughout the northern area and in nearshore areas of central Biscayne Bay, suggesting an urgent need for land use and land cover management to reduce local nutrient wash-off from the watershed to the bay (Millette et al., 2019). Santos et al. (2014) established that freshwater discharges into nearshore areas (contaminated by anthropogenic disturbances) have resulted in the fragmentation of the spatial patterning of submerged aquatic vegetation, which is thought to influence the distribution, community composition, and behavior of marine fauna.

Besides the increased use of fertilizers and other chemicals that promote excessive nutrient contents in soils, the presence of septic tanks and stormwater-management exfiltration trenches augments nutrient loadings to the vadose zone and groundwater, which might subsequently impact nutrient concentrations in the adjacent bay (Chin, 2020). Along with the stormwater onsite retention systems that exists all over the urban area surrounding the bay, water flow is affected by water management structures (canals, waterways, gates, etc.) that directly modify quantity, quality, timing, and distribution of freshwater flows to the coast (Stabenau et al., 2015). One of the several canals that drains freshwater inputs into the bay is the Coral Gables Canal.

The Coral Gables Canal is a waterbody 15.70 km long that collects waters from an 18.25 km^2 watershed. Its waters run southeast through Coral Gables, Florida, draining into Central Biscayne Bay. In rigor, the portion of the canal that is close to Biscayne Bay is a waterway. For brevity, in this study the whole water body will be identified as Coral Gables Canal. Water flow in the canal is interrupted by a control structure (Gate G93T), which is located 6.47 Km inland. The gate opens intermittently during the rainy season, having little to no flow during the dry season the water movement in the lower segment of the canal is governed almost entirely by tidal forcing (Bouck, 2017). Land use in the watershed is primarily residential and commercial. Nutrient concentrations in the canal display significant positive correlations to urban areas, population density, and the proximity to storm water drains (Bouck, 2017). Understanding Coral Gables Canal water quality processes would help comprehending the physical and chemical characteristics that govern nutrient loading into Biscayne Bay. Several other coastal watersheds pour waters into the bay through similar canals or waterways. A quantitative characterization of in-stream hydrodynamics and water quality processes taking place in the Coral Gables Canal would serve as a blueprint that can be used for assessing similar processes in the area surrounding Biscayne Bay.

This document presents a detailed description on the development of a hydrodynamic and water quality model for Biscayne Bay and the Coral Gables Canal. While the development of the hydrodynamic portion is almost complete, modeling of the water quality processes is still in process. However, being the transport of water one of the main drivers of water quality processes, this document also presents preliminary results of water quality simulations for the canal and the bay based on observed data and educated assumptions.

2. Geographical scope

Although the main focus of this study is the Coral Gables Canal, the geographical scope has been extended to include Biscayne Bay because the hydrodynamic regime and water quality processes occurring in the canal strongly depends on the bay processes.

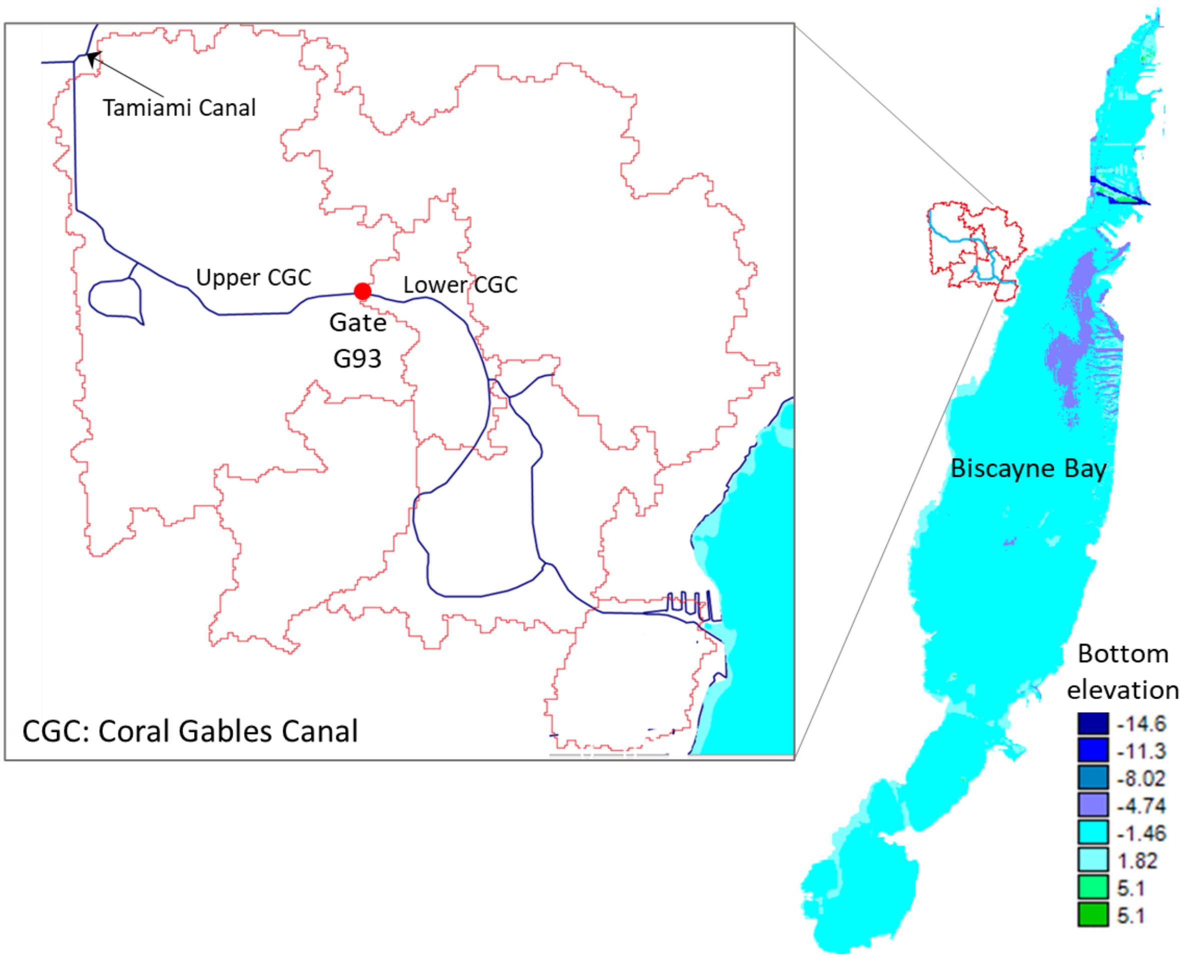

Figure1. Geographical scope of the study. The Coral Gables Canal, its watershed and the location of the canal outfall are shown.

Figure 1 shows the geographical boundaries for the study. Biscayne Bay is a coastal water body of approximately 1100 km^2. Its mean bottom elevation (relative to mean sea level) is approximately -2.90 m, and the minimum bottom elevation -15.5 m. The Coral Gables Canal (CGC) has a length of 15.70 km, spanning from its outfall to the bay up to its confluence with the Tamiami Canal. The Coral Gables Canal collects waters from an 18.25 km2 watershed. Water flow is interrupted by a control structure (Gate G93T), which is located 6.47 km inland. The gate divides the canal into two segments: upper CGC and lower CGC. The flow of water in the lower portion of the canal (lower CGC) is strongly influenced by Biscayne Bay tides. The upper Coral Gables Canal (upper CGC) pours water into the lower CGC only during strong precipitation events. The rest of the year the gate is closed, and water flows slowly towards the Tamiami Canal or remains stagnant.

Land use in the watershed is primarily residential and commercial. Figure 2 shows the distribution of land use in the watershed. Urban areas (represented by three types of residential area plus commercial and institutional urban use) are the predominant land use category (88.4%). Recreational areas (represented by parks and golf courses) cover 4.3 % of the watershed area. All other land use categories have minor coverages.

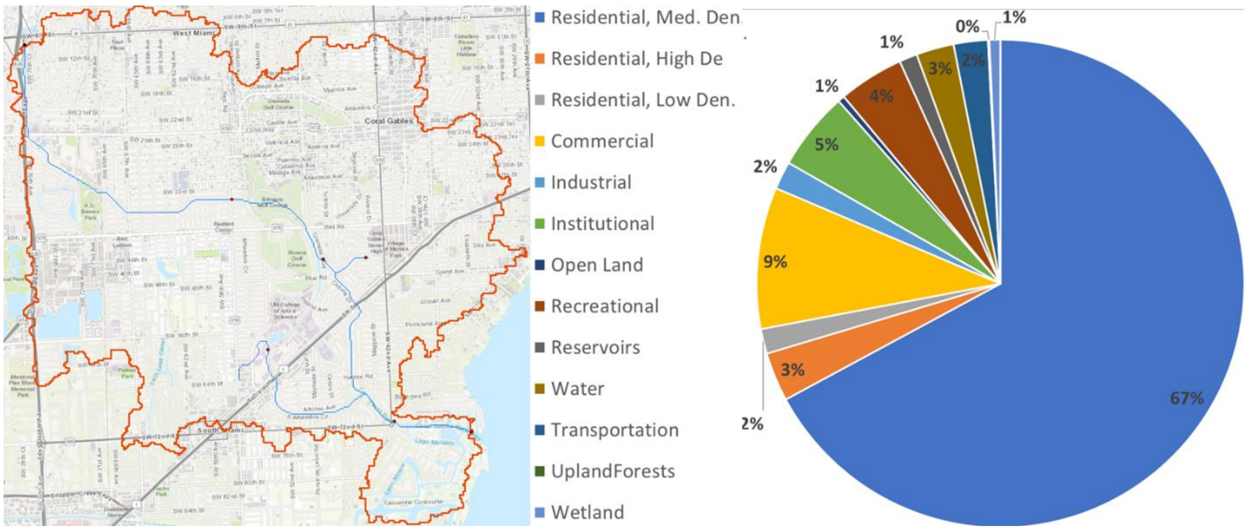

Figure 2. Land use. Almost 88 percent of the watershed that drains waters into the Coral Gables Canal correspond to urban settlements.

The watershed that encompass the Coral Gables Canal has a mostly flat topography. Elevation ranges between 1 m to 13 m above mean sea level, however the predominant elevations range between 1 m to 5 m within the catchment (Figure 3). Slopes of the terrain are between 4% to 5%. Soils are karstic throughout the study area.

Figure 3 shows the location of septic tanks within the watershed. The figure also shows the location of septic tanks within and out of the watershed. As shown, the density of septic tanks is very high in the residential areas. Also, the use of exfiltration trenches as stormwater onsite retention systems all over the urban area along with stormwater pipes, directly modify quantity, quality, timing, and transport of water and contaminants from the watershed to the Coral Gables Canal, and consequently greatly affect the transport of water and contaminants to the bay.

As described above, a quantitative representation of hydrodynamics and water quality processes in the study area faces the following challenges:

- Capturing the transport of water and contaminants from the watershed (non-point sources) to the Coral Gables Canal (CGC).
- Modeling hydrodynamic regime and in-stream water quality processes in the upper portion of the CGC, where water moves bidirectionally or is stagnant depending on the season of the year

- Modeling the hydrodynamic regime and in-stream water quality processes in the lower segment of the CGC that is strongly influenced by the Biscayne Bay tidal regime and also by the freshwater inputs from the watershed or (intermittently) from the upper portion of the CGC.

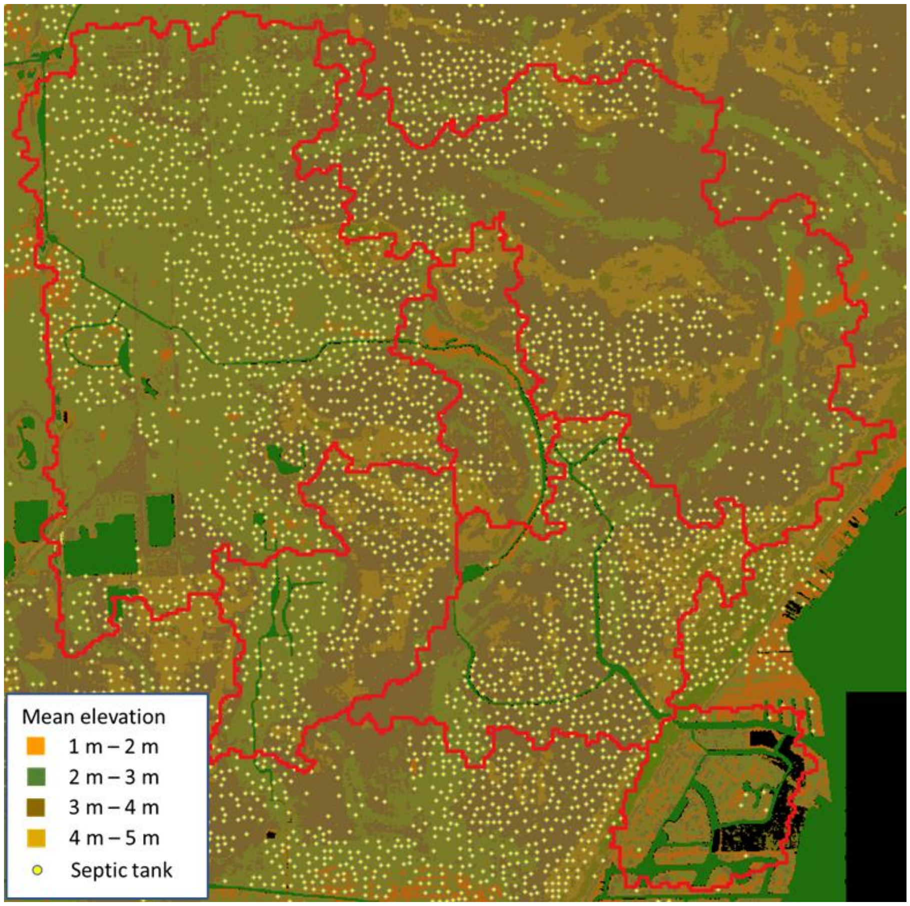

Figure 3. Topography in the Coral Gables Canal Watershed. Septic tanks in the area are represented as yellow dots.

3. Computational approach

The computational strategy that is being followed to quantitively represent the processes described in previous sections is to model first the movement of water (hydrodynamics) in Biscayne Bay and the lower segment of the Coral Gables Canal (CGC). Initially, rough estimates of inputs from stormwater pipes that drain into the lower CGC are used. Since the hydrodynamic regime of the lower CGC is dominated by tidal influences, modeling of this canal segment will represent adequately the transport of water albeit the rough estimates of the inputs from the stormwater pipes. Data from water quality stations located in the bay and data reported in the literature will be used to estimate water quality processes in the bay and the CGC. Then, the modeling task will be focused on the upper portion of the CGC including the intermittent operation of gate G93T, using rough estimates of water and contaminant inputs from the watershed. A third phase of the modeling of the study area will include the quantification of the watershed processes. In this phase, the inputs of water and contaminants to the CGC will be estimated using an existing hydrologic and water quality model of the watershed.

3.1 Basic input data

3.1.1 Bathymetry, topography and bottom roughness

The bathymetry data set used in this study correspond to a 1/3 arc-second Mean Lower Low Water bathymetric DEM produced by NOAA's National Ocean Service (NOAA/NOS, 2020), based on hydrographic survey data for Biscayne Bay. The bathymetric data (provided as a NETCDF data cube, NAVD) was geo-processed and projected to UTM (Zone 17 North, WGS84) coordinates. The resulting data raster (horizontal spatial resolution 9.27 m x 9.27 m, vertical accuracy 0.01 m) is shown in Figure 1. The bathymetric information contained in the resulting raster was the basic geo-spatial data used for generating the computational grid of Biscayne Bay.

The topographical data used to characterize the topography of the watershed and the bathymetry of the Coral Gables Canal was a 5 m cell size Digital Elevation Model (DEM). The elevation units, expressed in meters, have NAVD88 as reference datum. The dataset is provided in Albers Equal Area Conic HARN projection by the University of Florida GeoPlan Center (2020). Figure 3 shows the topographical features within the watershed.

3.1.2 Tidal, river stage, and wind data

Hourly data for water surface elevation (WSE), air temperature, wind speeds and wind direction were obtained from NOAA (2020). Data corresponding to Virginia Key Station (Figure 4) for five years (January 2015 through December 2019) were obtained. In this progress report, hourly data for the period January 1, 2019 to August 30, 2019 were used during hydrodynamic calibration. Hourly data from January 1, 2015 to December 31, 2015, were used for verification and validation of the hydrodynamic model output. All data were transformed to the metric system, NAVD vertical reference, and GMT zone. Wind and temperature data at Virginia Key Station are collected at 8.5 m above mean sea level.

Independently collected data for river stage were used for comparing the model-generated water surface elevations. Data from the South Florida Water Management District's DBHYDRO platform (SFWMD, 2020) were downloaded for the period January 2015 through December 2019. These data were used during calibration, verification, and validation of the hydrodynamic model output. Data from the following DBHYDRO's river stage stations were used: MRMS4, S123_T, G93T (Figure 4).

3.1.3 Water quality data

Water quality data for this study were obtained through the DBHYDRO platform (SFWMD, 2020). The collected datasets corresponded to the following DBHYDRO Stations: SP01, MW01, BL01, PR01 and MR01. These water quality stations are located at the outfall of the canals that significantly contribute fresh water and contaminants to the bay (as reported by Millette, 2019). Figure 4 shows the locations of the water quality stations. The data extracted from each of these stations were: ammonia-nitrogen, nitrate-nitrogen, total phosphate, and water temperature. The temporal resolution of the data is monthly.

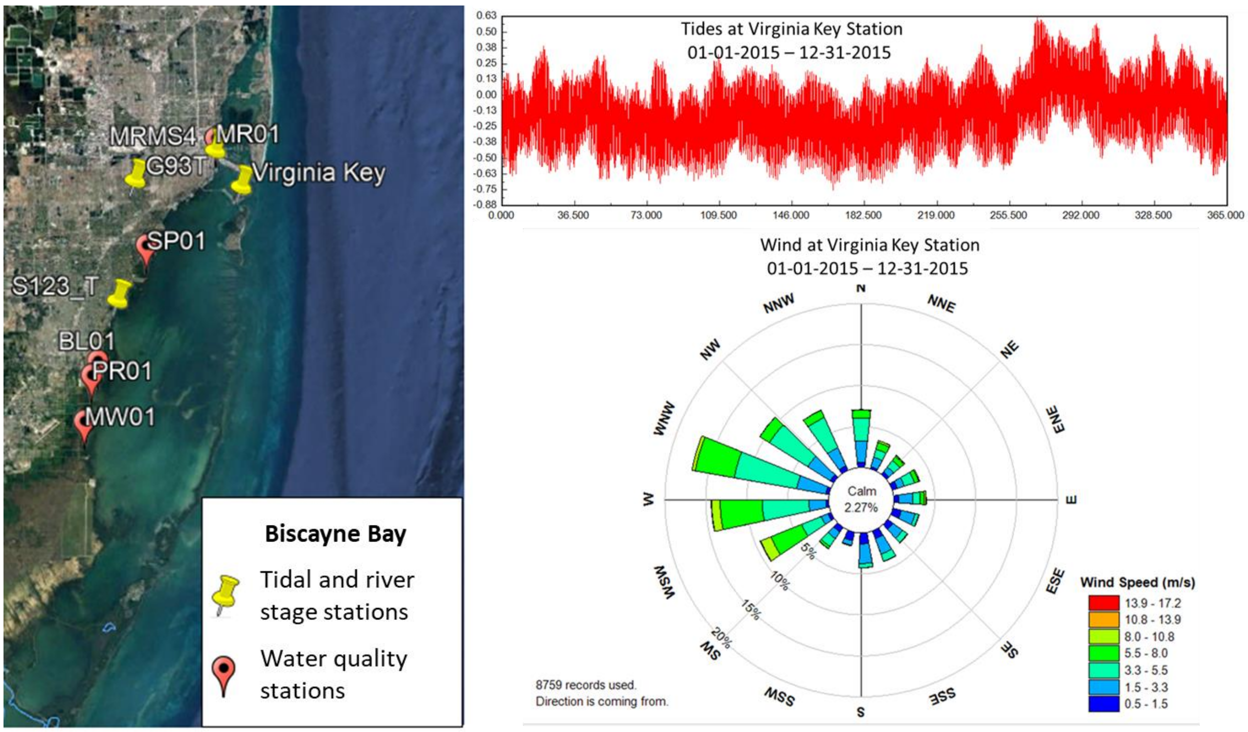

Figure 4. Geographical locations of tidal, wind, river stage, and water quality stations in the study area.

3.2 Choosing the computational tool

In addition to acquiring current and updated basic information characterizing the study area, several computational tools were explored to build model representations of the hydrodynamic and water quality processes taking place in Biscayne Bay and the Coral Gables Canal. Figure 5 summarizes some of the trial model representations of the bay and the canal.

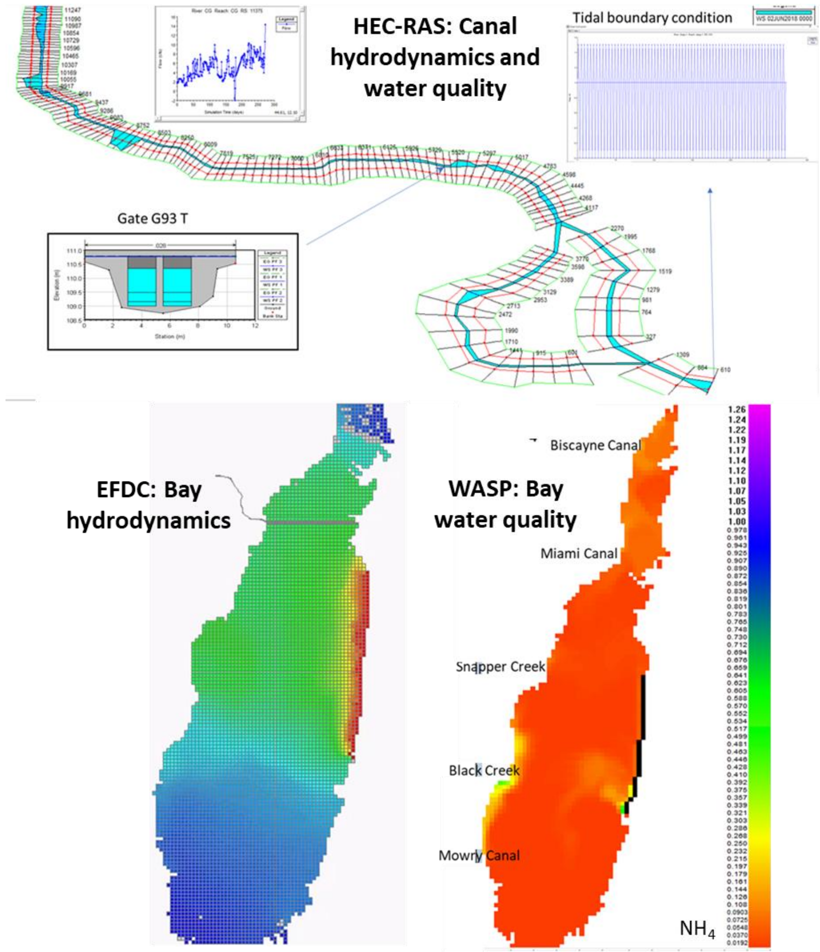

Figure 5. Initial modeling trials for estimating water quality and hydrodynamics in Biscayne Bay and the Coral Gables Canal.

Initially, a HEC-RAS hydrodynamic and water quality model for the Coral Gables Canal was developed, intended to be loosely linked to an EFDC hydrodynamic model of Biscayne Bay. Water quality in the bay was estimated using WASP, after transferring the hydrodynamics calculated by EFDC, also through a loose link. However, the canal model (HEC-RAS) did not include salinity in the estimation of the hydrodynamic regime or water quality. This limitation was overcome extending the EFDC bay model to include the portion of the canal that is under tidal influence (Gate G93T). However, the representation of only one portion of the canal with HEC-RAS forced to re-assess the conceptual model and computational representation of the processes in the canal and the bay. Therefore, in search of a wholistic representation of the hydrodynamic and water quality processes in the canal, a tentative CE-QUAL W2 model for all the canal was developed which was able to estimate hydrodynamics and water quality, including the effects of salinity on both set of sets of processes. Nevertheless, CE-QUAL W2 is not capable of modeling channel bifurcations and hydraulic structures as efficiently as HEC-RAS. Also, loose linking proved to be not efficient in terms of processing time and conceptual representation of the processes.

The computational exploration described above identified the need to find a computational tool that would be able to model the whole geographical domain of interest (Biscayne Bay and Coral Gables Canal), and all physical and chemical processes involved (hydrodynamics and water quality) simultaneously. An existing hydrodynamic and water quality modeling system, EFDC + (DSI, 2020) consisting on a seamless integration of EFDC (hydrodynamics) and HEM-3D (water quality) seemed to be a good alternative for a simultaneous modeling and simulation of the bay and canal.

3.3 Application of the EFDC+ (EFDC-HEM3D) modeling system to the study area

Applying the EFDC-HEM3D system for generating an efficient model representation of the study area required iterating with the following variables: computational grid spatial resolution, location of boundary conditions, curvilinear versus cartesian coordinates, numerical criteria (time-step, numerical algorithm, etc.). The resulting computational representation of Biscayne Bay and the Coral Gables Canal is shown in Figure 6.

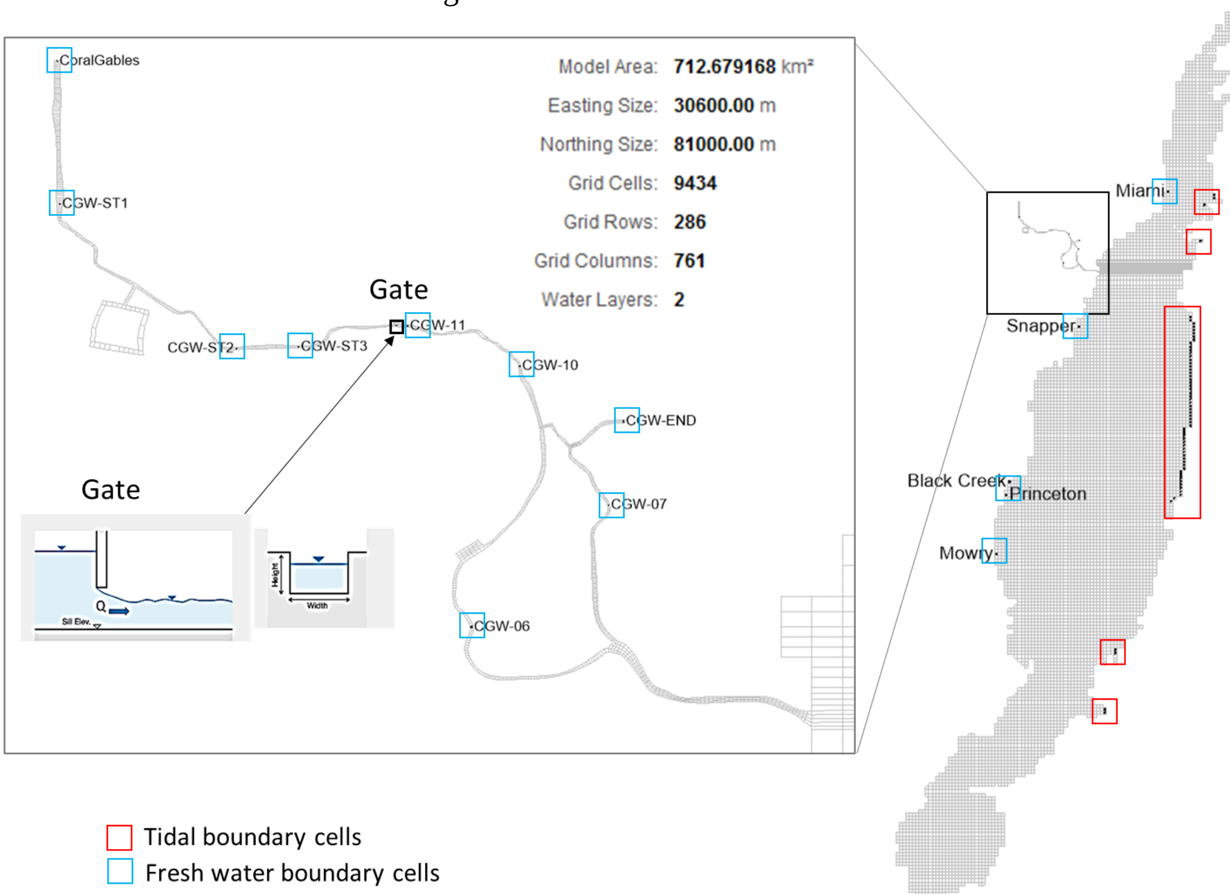

Figure 6. Computational grid for the study area. Open ocean boundary cells and freshwater boundary cells are shown. A cartesian grid representing Biscayne Bay connects to a curvilinear grid representing the Coral Gables Canal.

The computational mesh shown in Figure 6 consists of over 9400 grid cells. The bay is represented in cartesian coordinates and the canal consists of curvilinear cells. To have an efficient transfer of information between the bay portion and the canal portion, cell sizes near the outfall of the canal to the bay were gradually decreased until reaching similar order of magnitude in size as the cells of the canal. The computational mesh includes a representation of gate G93T (located on Coral Gables Canal), which operation is simulated according to the rules of operation reported for the hydraulic structure by DBHYDRO.

Boundary cells are also shown in Figure 6. Tidal boundary cells are located at the eastern borders of the grid and impose seawater inputs to the system using data from Virginia Key Station (tidal and wind). Fresh water boundary cells were implemented for Mowry, Princeton, and Miami canals. Black Creek and Snapper Creek are also included as freshwater inputs to the system.

4. Preliminary results

4.1 Hydrodynamic calibration, verification, and validation

Hydrodynamic calibration was performed comparing simulated and observed water surface elevation data at gate G93T (on Coral Gables Canal). Since this study is focused on the water quality and hydrodynamic regime in the canal, it was considered paramount to have a good representation of in-stream processes specially within the portion of the canal that is under tidal influence. Calibration was performed for short periods of time and verification of water surface elevations at the gate was undertaken for long simulation periods. Validation, on the other hand, was done comparing simulated water surface elevations at two stations close to the Coral Gables Canal outfall to the bay: tidal station MRMS (located at the outfall of Miami canal), and station S123 (located at the outfall of Cutter canal).

Table 1. Table 1. Statistical indicators of fit and error.

Root-mean-squared-error to standard deviation ratio	$RSR = \frac{RMSE}{STDEV_{Obs}} = \frac{\sqrt{\sum_{i=1}^{n}(Y_i^{Obs} - Y_i^{Sim}).^2}}{\sqrt{\sum_{i=1}^{n}(Y_i^{Obs} - Y_i^{Mean}).^2}}$
Nash-Sutcliffe efficiency	$NS = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{Obs} - Y_i^{Sim}\right).^2}{\sum_{i=1}^{n}\left(Y_i^{Obs} - Y_i^{Mean}\right).^2}$
Kling-Gupta efficiency	K-G = $1 - \sqrt{\left(\frac{Y_{Sim}^{Mean}}{Y_{Obs}^{Mean}} - 1\right)^2 + \left(\frac{STDEV_{Sim}}{STDEV_{Obs}} - 1\right)^2 + (R-1)^2}$
Y_i^{Obs} = Observed SST concentration Y_i^{Sim} = Simulated SST concentration Y_{Obs}^{Mean} = Mean of observed SST concentration Y_{Sim}^{Mean} = Mean of simulated SST concentration, n = Total number of daily SST concentrations	

Figure 6 shows results of hydrodynamic calibration undertaken for the period 01-01-2019 to 06-16-2019. As shown, statistical indicators of fit show that the calibration is successful (R^2 = 0.89, NSE = 0.77, and K-G = 0.37). Similar results are achieved with respect to the indicators of error and bias: PBIAS = -6.6 % and RSR = 0.32, respectively. In general, the model slightly underestimates water surface elevations, however, the low statistical error shows that the underestimation is acceptable. Also, it should be noted that during periods of time in which the gate is opened and water flows from the upstream portion of the canal, the underestimation is more evident. However, during the verification phase, the intermittent operation of the gate (that lets water flow from upstream of the gate) was included in the simulation. Table 1 summarizes formulae for all statistical indicators.

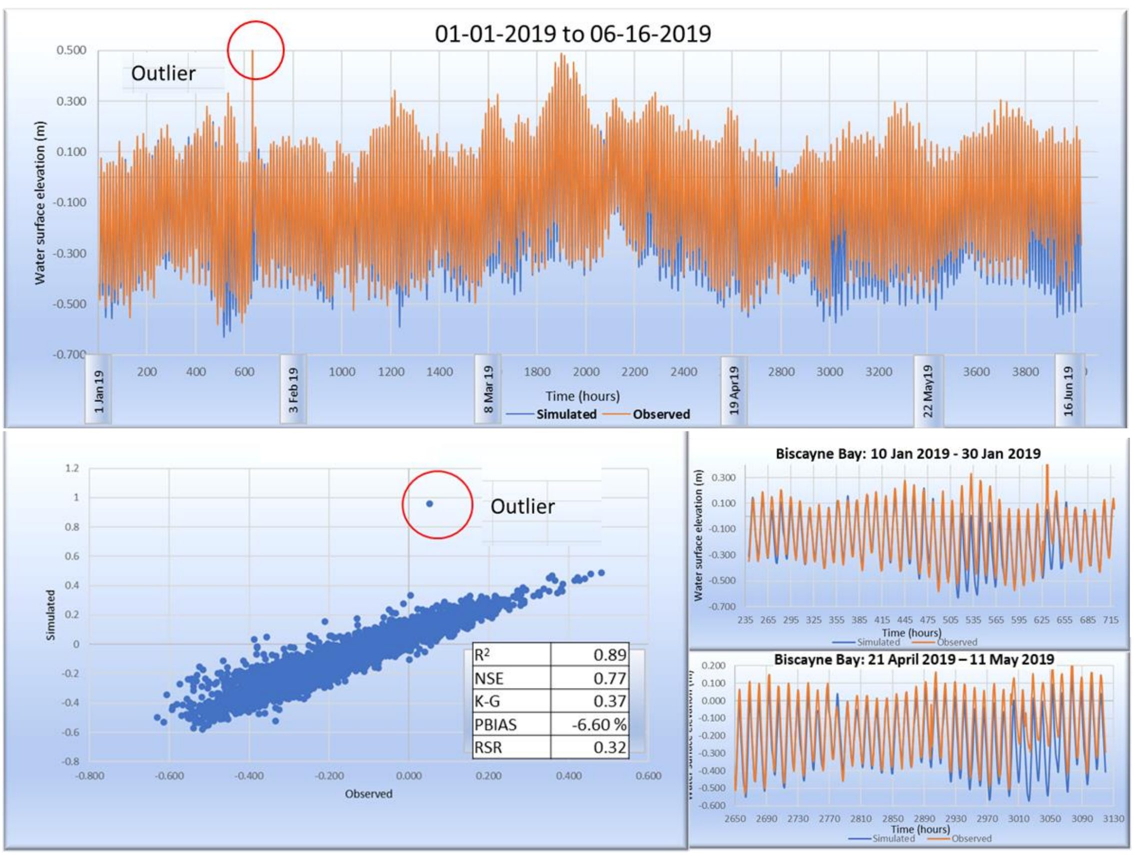

Figure 7. Hydrodynamic calibration. Simulated output for the period 01-01-2019 to 06-16-2019 was compared to observed water surface elevations at Gate G93T. Statistical indicators show that the model replicates observed data.

Verification and validation of model-simulated water surface elevations is presented in Figure 8. The simulation period was 01-01-2015 to 12-31-2015, at hourly time-step. As stated in previous sections, during the validation phase the simulated output was compared against observed data at the following stations: MRMS4 (located at the outfall of Miami canal), and S123T (located at the outfall of Cutter canal). The model output at Gate G93T is verified comparing it for a more extended period of time than that used during calibration (01-01-2015 to 12-31-2015).

As shown in Figure 8, the calculation of statistical indicators of fit provided coefficient of determination values (R^2) greater than 0.93, and the Nash-Sutcliffe (NSE) efficiency values greater than 0.83. These statistics indicate that the hydrodynamic model provides good estimates of water surface elevations at the control stations G93T, S123T, and MRMS4. Kling-Gupta efficiency values, which is an indicator of goodness of fit as well as bias, are also for G93T and MRSM4 stations (K-G > 0.23). K-G for station S23T, however, could be improved. Nevertheless, for all control stations the statistical error es small (RSR < 0.41). Although the water surface elevations output by the model for central Biscayne Bay slightly underestimate observed data, the model output for northern Biscayne Bay is very good.

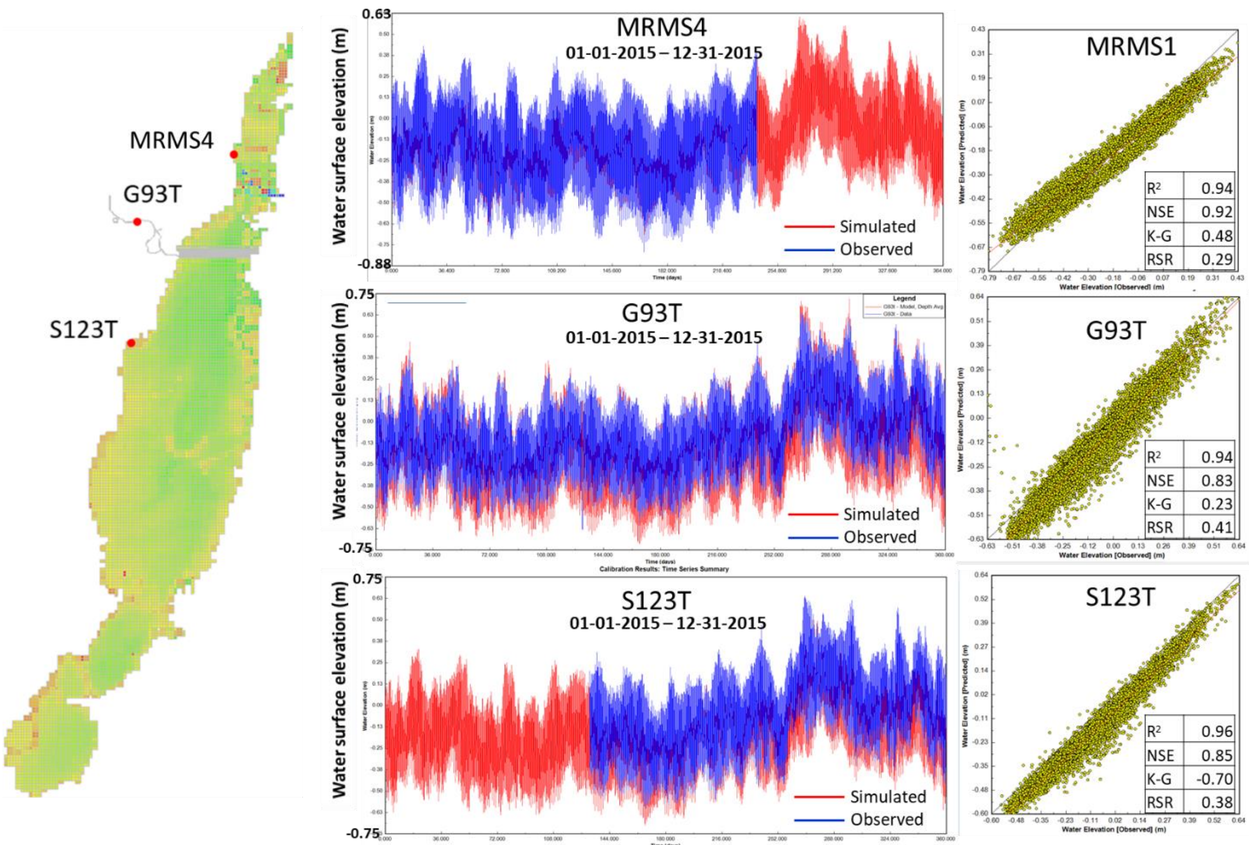

Figure 8. Validation and verification of model generated water surface elevations. Verification of the model output is performed comparing its estimations to observed data at G93T control station. Validation of the model is done at control stations S123T and MRMS4.

4.2 Initial water quality exploration

4.2.1 Biscayne Bay

With the calibrated and partially validated hydrodynamic model, a simulation of water quality within the bay was performed. To achieve this, the water quality subroutines of EFDC+ (HEM3D) were activated. The objective of this experiment was to ascertain if with the introduction of observed water quality data for year 2015 at the locations shown in Figure 4, the model was able to reproduce water quality spatial trends and concentration values reported in the literature. Figure 9 shows a spatial comparison of model simulated output and results reported in Millette et al. (2019).

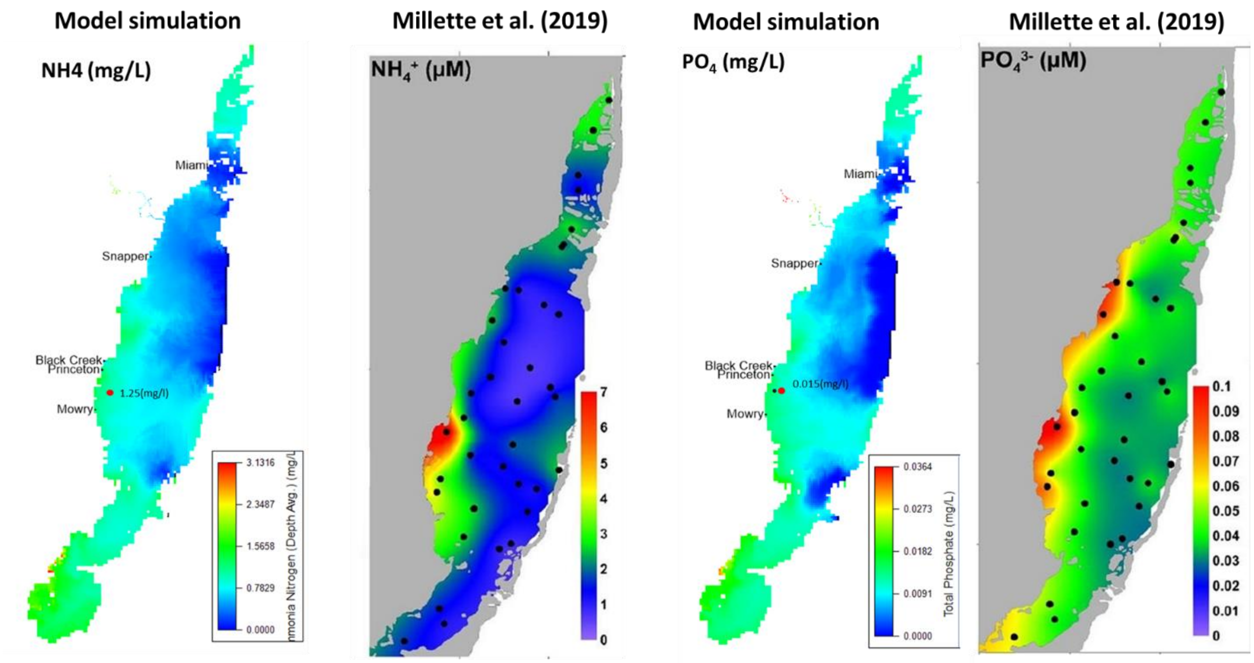

Figure 9. Comparison of the simulated spatial distribution of NH_4 in Biscayne Bay. The simulated output is compared to spatial distribution of NH_4reported in the literature.

Figure 9 shows that the model captures the spatial distribution of NH_4 at central and northern Biscayne Bay. However, the model simulates accumulation of NH4 in the southern portion of the that is not reported in Millette et al. (2019). Since the hydrodynamic model was calibrated and validated for the central and northern sectors of the bay and in-stream water movement is one of the main factors for contaminants transport, it could be expected that NH4 concentrations for southern portions of the bay would not be simulated appropriately. Steps are being taken on improving hydrodynamic calibration by including water surface elevations measured at stations located in southern Biscayne Bay. Moreover, the estimation of kinetic rates will also be improved to account for a better simulation of the in-stream water quality processes. Figure 9 also shows a comparison of the spatial distribution of phosphate in the bay. As shown, the model captures the concentration distribution slightly better than that of NH_4. Although the concentration values in Millette et al. (2019) are given in μM/L, if conversion of units are performed, the order of magnitude for the NH_4 and PO_4 concentration values output by the model is adequate.

4.2.2 Coral Gables Canal

Bouck (2017) reports trends in several water quality constituents for the Coral Gables Canal. Using the concentration values reported in that research, an exploratory comparison of the water quality output generated by the model to observed data is performed. Figure 10 shows the spatial distribution of NH_4 simulated by the model compared to observed data reported in Bouck (2017). Although the water quality model in the canal is using rough estimates of boundary concentration values and flows, the model replicates the trend of decreasing NH_4 concentrations along the lower portion of the CGC, as water approaches the canal outfall.

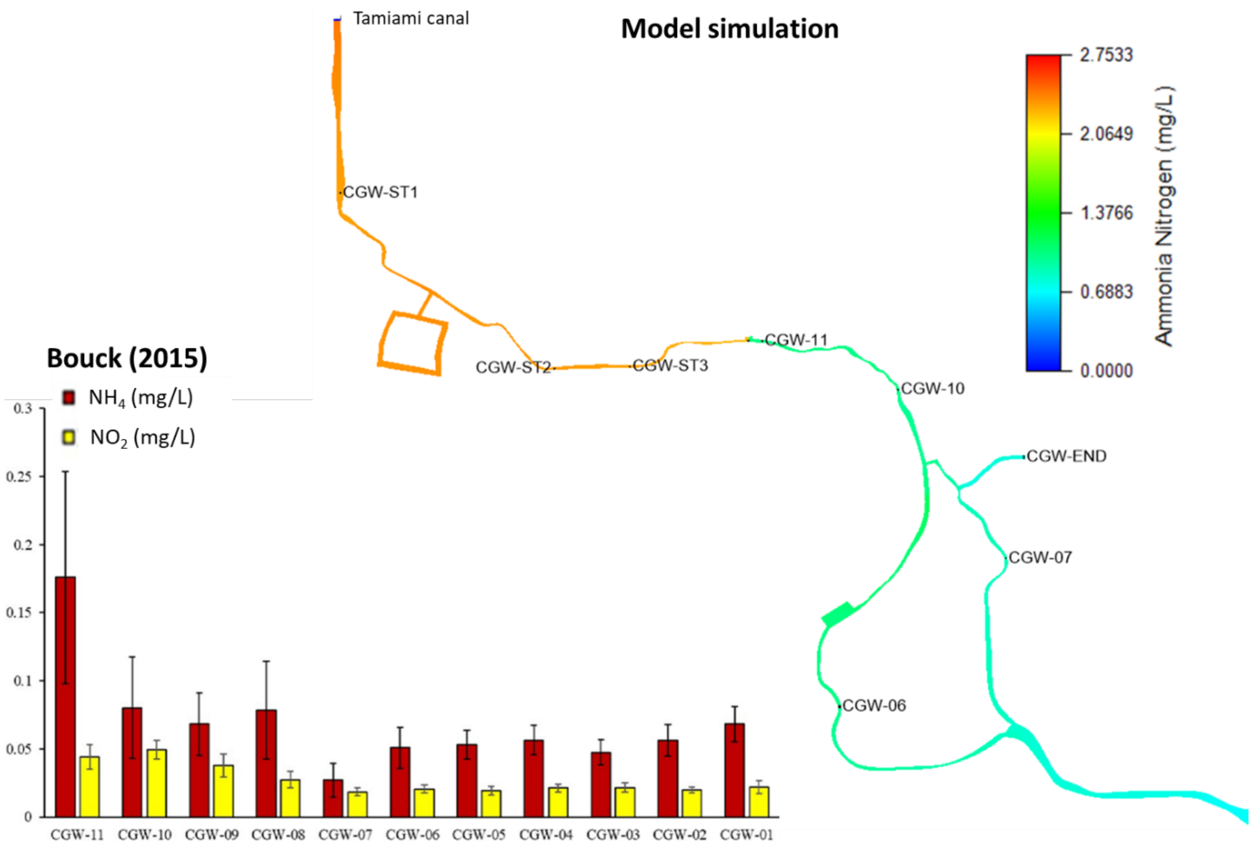

Figure 10. Comparison of the simulated spatial distribution of NH4 in the Coral Gables Canal. The simulated output is compared to spatial distribution of NH_4 reported in the literature.

Figure 11 shows model-simulated results for nitrate concentrations along the Coral Gables Canal. The model correctly captures the spatial distribution of NO3 concentrations in the lower segment of the canal. The concentration values are of the same order of magnitude as those reported by Bouck (2015). Nevertheless, the concentration values for all water quality constituents simulated by the model must be improved. This will be achieved when the watershed model is operational for calculation of more realistic inputs of flow and contaminant concentrations to the canal.

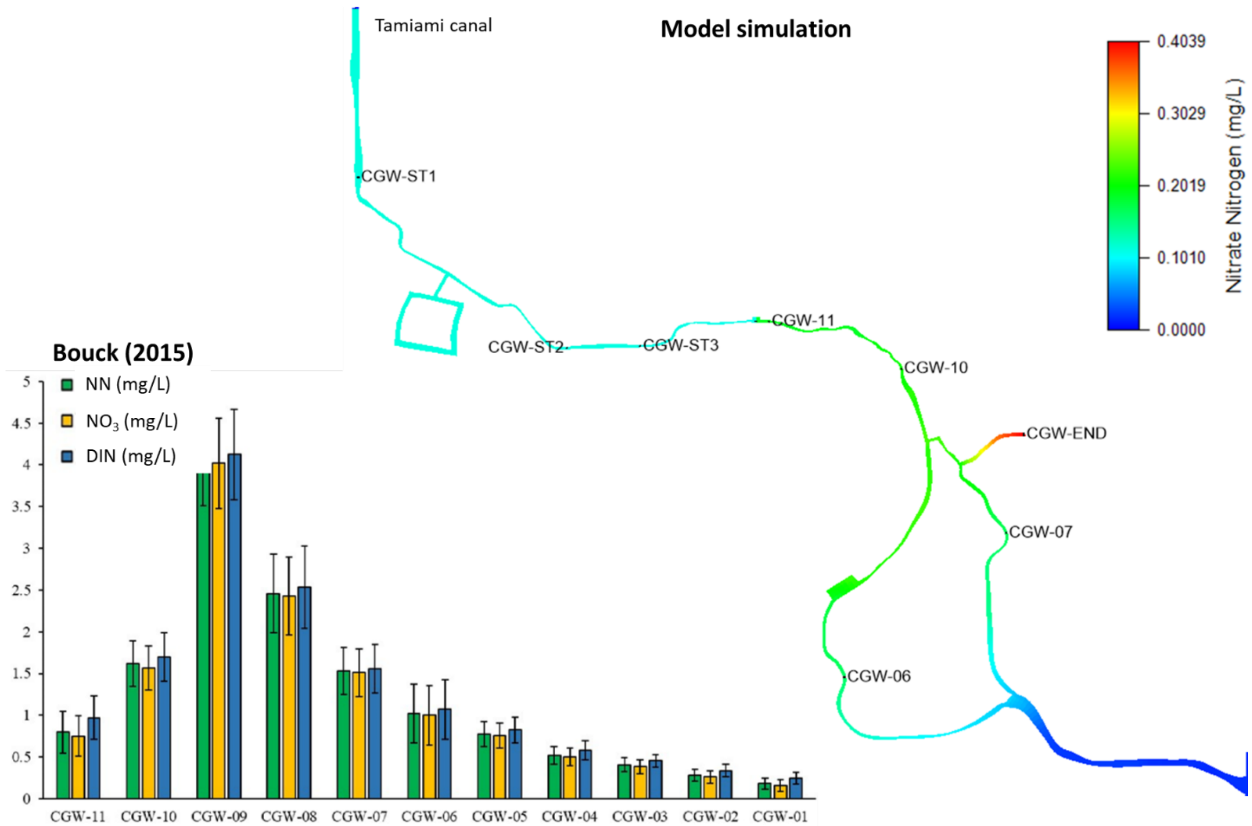

Figure 11. Comparison of the simulated spatial distribution of NO_3 in the Coral Gables Canal. The simulated output is compared to spatial distribution of NO_3 reported in the literature.

5. Next steps

An improvement of hydrodynamic modeling for the southern portion of Biscayne Bay is in progress. Observed data stations located at the south of the bay that report water depths (not water surface elevations) will be used for improving the hydrodynamic model. Since this study is simulating hydrodynamics and water quality processes at hourly time-step, it requires data of the same temporal resolution. Nevertheless, efforts are concentrated on using available data by disaggregating the data values. This is especially necessary for water quality data that are collected monthly.

Although there are not enough data for simulating benthic processes, they are being explored and implemented into the model basing this effort in data and rationale reported in the literature.

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