Numerical Model Flushing Experiments

Final Report

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Executive Summary

Numerical model experiments using the US Army Corps of Engineers (USACE) Coastal Modeling System (CMS) were conducted to assess the potential for modifications of the causeways and bridge structures of Florida State Routes (SR) 528 and 520 to enhance the flushing rates of the north compartments of the Banana River and in adjacent North Indian River Lagoon (IRL) compartment. The CMS was set up to reproduce the physical conditions of 2015 to assure that real physics are represented in the model. Driving forces at the boundaries of the model include water level measurements, gauged freshwater inflows, and wind velocity. The topography of the model is derived from LiDAR surveys and in-situ surveys. The measured data sets used to drive the model are fully described in a report on the Indian River Lagoon hydrodynamic and water quality model by Zarillo and Listopad (2017).

A total of nine model tests were performed representing conditions of the existing configuration and a series of hypothetical bridge spans over the Banana River and the IRL. Three model tests included multiple flow relief structures embedded in the SR 528 and SR 520 causeways. The model tests were run by specifying a numerical tracer dye concentration of 20 parts per thousand (ppt) throughout the model domain and then tracking the reduction in dye concentration as the model calculation proceeded. Flushing is promoted in the study area by exchanges with the coastal ocean though Sebastian Inlet, freshwater inflows, and mixing and transport from winds.

Results of the model runs indicate that modifications of the bridge and causeway structures would have detectible influence on flushing rates in the Banana River and North Indian River Lagoon. The model results indicate that the configurations involving enhanced bridge spans have a measurable influence on dispersion of the dye in the numerical experiments. Longer bridge spans over the Banana River along SR 528 combined with long bridge spans over SR 520 resulted in predicted declines of 17% in the dye concentration in the Banana River compartment between SR 528 and SR 520 by the end of the 340-day model runs. This is compared to predicted declines in tracer concentration of about 7.7% in the same compartment under existing configuration. The net improvement in flushing action in the Banana River compartment between SR 528 and SR 520 is predicted to be on the order of about 10% for model cases that combine bridge spans for both roads. The net improvement in flushing in the Banana River compartment immediately to the north of SR 528 is predicted to be on the order of 5% as long as bridge spans are present on both state roads. A fundamental conclusion of this study is that significant improvement in flushing of the Banana River compartments and the adjacent IRL compartments would require bridge spans on SR 520, as well as SR 528.
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1.0 Introduction and Goals

Preliminary model circulation experiments performed in 2013, and extended to a larger project in 2015, showed that structural modification of the Indian River Lagoon (IRL) geometry could improve flushing rates and reduce residence times. Prior experiments included hypothetical tidal inlets, pump stations, and a hypothetical weir structure to introduce continuous or episodic inflows to the IRL from the coastal ocean.

In the present project, the modeling experiments are limited only to hypothetical cases that modify the bridge and causeway structures of SR 528 and SR 520 as they cross the Banana River. In addition to these primary targets of modification, model cases also include combinations of the causeway and bridge structures that cross the north compartment of the IRL to the west of the Banana River.

The numerical modeling platform applied in this study is the US Army Corps of Engineers (USACE) Coastal Modeling System (CMS) as described in the next section. CMS is capable of including wave propagation, sediment transport, and morphologic change over time along with hydrodynamic circulation. Since wind data are available from metrological station in the IRL area the model option for wind generated wave energy was combined with prediction of circulation. This allows the effects of wind waves to contribute to mixing and transport along with wind and tide generated circulation. The options for sediment transport and morphological changes were not included.

The goal of applying numerical tests of flushing rates in the Banana River and the north and central IRL compartments, is to identify the potential for improving the state of water quality by promoting more rapid flushing of sub-compartments between causeway structures. The options for cutting small tidal inlets was not included in this work due to the potential impacts on the littoral sediment budget by impoundment of sand in shoals generated by strong flows though tidal inlets and sand impoundment at jetty structures used to stabilize inlets. Although the likely side effects of promoting exchanges in terms of morphodynamics are not considered in this project, model forcing was kept as physically real as possible by including real time series of water elevation, freshwater, inflows, and wind velocity at model boundaries.

2.0 Model Features

The CMS was developed by the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). CMS is a coupled group of numerical models for calculating waves, circulation, sediment transport, constituent transport, and morphology change. Calculations can be performed for flows generated by tide, wind, waves, river discharges, and changes in salinity. A significant study for model verification and validation of the CMS is documented in Demirbilek (2011), Lin (2011), Sanchez (2011a),

CMS-Flow is a 2-D finite-volume model that solves the mass conservation and shallow-water momentum equations of water motion. CMS-Flow is forced by water surface elevation (e.g., from tide), wind and river discharge at the model boundaries, and wave radiation stress and wind field over the model computational domain.

CMS-Flow is presently capable of 2-D transport computations in both the explicit and implicit solvers. The simulation of constituent transport can often require a three-dimensional (3-D) solution due to the presence of strong vertical gradients that can influence the flow. It is therefore important to understand the limitations of 2-D transport simulations, and apply them only when the assumptions inherent in 2-D simulations are valid. Typically, 2-D salinity simulations are valid in a well-mixed water column. These conditions are usually met for shallow bays with open exchanges to the ocean or gulf, and strong tidal signals and sufficient wind energy to provide the vertical mixing. Thus, it is assumed that the IRL system is largely well mixed in the vertical and over time scales of the computations performed in the study, which are on the order of one year.

3.0 Model Setup

3.1 Grid Generation

A model computational grid was constructed covering the Banana River, a north compartment of the IRL, and extending to the Wabasso area within Indian River County where a measured water level boundary condition is available to help drive the model. Figure 1 illustrates the area covered by the model computational grid.

3.2 Model Boundary Conditions: Water Level Discharge and Wind Time Series

For the existing condition and all other model runs over the grid (Figure 1), water level boundary conditions were set at the entrance of Sebastian Inlet and at the Wabasso Bridge in Indian River County, which marks the southern end of the model grid. The selected model time period for model runs is calendar year 2015, which includes the most complete time series of data for boundary conditions. Figure 2 shows the monitoring stations maintained by the St Johns River Water Management District (SJRWMD) and the U.S. Geological Survey (USGS) from which most of the model boundary conditions can be extracted.

Freshwater discharge time series were applied at the Eau Gallie River, Crane Creek, and Turkey Creek tributaries to the IRL. In the Sebastian River, the gauged discharges from the S-157 structure and the Fellsmere Canal were combined. Figure 3 shows model details around the
Sebastian area including water level and discharge inputs at CMS boundary cell strings that define the model boundary conditions.

Figure 1. Configuration of Model Grid
Figure 2. Location of monitoring stations throughout the north and central Indian River Lagoon.

Figure 3. Model grid details and boundary conditions in the Sebastian Inlet area.
CMS flow will assimilate wind data as multiple inputs over selected cells or as global input over the entire model domain. In this study two wind records from 2015 were applied including data from a meteorological station maintained by the SJRWMD in the Banana River area and data from a station located at Sebastian Inlet maintained by the Florida Institute of Technology.

4.0 Model Verification

Comparisons have been made between measured and model water level data from locations within the IRL. This is necessary since the water level time series that force the model from the coastal ocean and from the atmosphere are continually updated from the original model setup. There are three high quality water level data sets available within the system due to the efforts of Dr. Robert Weaver of Florida Tech to maintain pressure sensors at the locations shown in Figure 4. At present, these data sets are not leveled with respect to the NAVD88 vertical datum. However, the model and measured data can be demeaned and reset to a time series average of zero. For example, Figure 5 shows a comparison between the data and model for a monitoring station at Lansing Island in Indian Harbour Beach near the south end of the Banana River. The comparison period is 2015 and the records show the extremes of sea level shifts, primarily caused by changes in Gulf Stream Flux (Zarillo, 2017). The model and data are closely matched and have an R-square comparison of 0.80 or a correlation of about 0.89 (Figure 5). This is considered very good given the limitations of both the model calculations and the pressure sensor technology at the monitoring stations. The model-data comparison at the Sebastian station is also good, as shown in Figure 6. Here, the R-square value is 0.86 for a correlation of about 0.93. Both model and monitoring data at these stations clearly show the major features of the water level changes in the IRL at times scales of a few days and longer that are driven by changes in the coastal sea level. The fact that the model reproduces these sea level changes well within the distal reaches of the IRL system provides assurance that the hydrodynamics of the model are correctly reproducing nature.
Figure 4. Location of Florida Tech water level monitoring stations in the Indian River Lagoon.

Figure 5. Model and measured water level comparison at Lansing Island.
5.0 Model Run Configurations

Table 1 lists the model configuration for each of the model runs conducted in this study to evaluate flushing conditions. Each model run began with specifying an initial tracer concentration of 20 parts-per-thousand (ppt) throughout the model domain. Tracer concentration at the model boundaries was set to zero though each model run. The initial year-long runs were configured for existing conditions. Subsequent model configurations included bridge spans across the Banana River along SR 528 and SR 520 as indicated by Model Runs 2 and 3 in Table 1. Model Run 4 applied the 528 and 520 spans to both the Banana River and across the IRL compartment to the west. This option is termed “4-span”. Model Run 5 includes two shorter spans along SR 528 rather one long continuous span. Likewise, Model Run 6 includes two shorter spans across both 528 and 520. These are the “double span” options. Model Runs 7 and 8 applied low elevation relief Structures in the SR 528 causeway (Model Run 7) and flow relief structures in both the 528 and 520 causeways (Model Run 8). Model Run 9 specified flow relief structures within the causeways that cross both the IRL and the Banana River. In Model Run 9, the number of relief structures within the SR 520 causeway crossing the Banana River was increased from 5 to a total of 7 in an effort to improve the flushing action beyond that observed in the results of Model Run 8.

In the following section of the report, results of each model test case are presented including a graphical representation of the model configuration and visualization of dispersal of the initial dye concentration of 20 ppt. The model results presented in this report are also
supported by an extensive electronic appendix that includes model test case graphics and animations of dye concentrations over the course of the model runs. In addition to visualization of the dye concentrations, animations of drogue movement though each model run are provided in the electronic appendix. The numerical drogues track the movement of selected parcels of water over time.

Table 1. List of model runs

<table>
<thead>
<tr>
<th>Model Run</th>
<th>Configuration</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Existing Configuration</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>2</td>
<td>528 Bridge Span</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>3</td>
<td>528 and 520 Bridge Spans</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>4</td>
<td>528 and 520 Four Bridge Spans</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>5</td>
<td>528 Double Spans</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>6</td>
<td>528 and 520 Double Spans</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>7</td>
<td>528 Flow Relief Structures</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>8</td>
<td>528 and 520 Flow Relief Structures</td>
<td>2015 340 days</td>
</tr>
<tr>
<td>9</td>
<td>528 and 520 Flow Relief Structures IRL and Banana River</td>
<td>2015 340 days</td>
</tr>
</tbody>
</table>

6.0 Model Results

Graphical presentations of the numerical flushing experiments are attached in an electronic appendix to this document for convenient review. The appendix includes a slide presentation that is linked to video files. A convenient video player is also included in the electronic appendix for frame by frame viewing of the animation files that show tracer concentrations at a daily update time scale. In order to provide a quantitative approach to evaluating the potential for each of the model test cases to produce enhance flushing effects, the project area is divided into compartments as shown in Figure 7. The compartments are bounded by morphologic variations in the IRL geometry and in part by one of the causeway structures cutting across the north Banana River and the IRL. Numerical monitoring stations, numbered according to the compartment in which they are located, are placed in the center of each compartment in order to extract a representative sample of the potential for flushing of the compartment and reduction of the tracer concentration over the course of each model run. Compartment 1 (Figure 7) is located to the south of SR 520 causeway in the Banana River. Compartment 2 is located between the SR 520 and SR 528 causeways, whereas compartment 3 is located to the north of the SR 528 causeway (Figure 7). Compartments 4 and 5 are located in the north IRL to the west of the Banana River (Figure 7). Compartment 4 is situated between the SR 520 and SR 528 causeway, whereas compartment 5 is located to the north of SR 528 as shown Figure 7. In the final analysis presented in the conclusions section of this report, the minimum
tracer concentrations found in each compartment are compared in table format, along with the percentage of net flushing improvement compared to the existing configuration.

Figure 7. Location of compartments and associated numerical monitoring stations from which time series of tracer concentrations can be extracted.

6.1 Model Run 1: Existing Configuration

Under the existing configuration short bridge spans and relief structures are embedded in the causeways that cross the Banana River and north compartment of the IRL as shown in Figure 8. The maximum bridge span of about 2,200 feet in length is on SR 528 as it crosses the IRL. SR 528 has spans of about 200 feet and 1000 feet linking the causeways that crosses the Banana River. State Road 520 includes a 1400-foot span in the IRL causeway along with a 170-foot relief structure on the west side of the IRL causeway. Over the Banana River, SR 520 includes a 220-foot-long relief structure on the west side of the causeway and a 650-foot span to the east. Within Sykes Creek there is a low bridge structure approximately 400 feet long that allows exchanges across the 520 causeways.
Figure 9 shows the concentration of numerical tracer dyes in the North Banana River and adjacent IRL compartment after 340 days of model simulation using the boundary conditions outlined in Section 3.2 of this report. A full visualization of the model run is provided in the electronic appendix including the movement of numerical drogues over the course of the model run. Generally, flushing time can be defined as the time required to drain a volume ($V$) through an outlet ($A$) with current velocity ($v$). The flushing time ($t_F$) concept for an estuary can be defined as the time needed to replace its freshwater volume ($V_F$) at the rate of the net flow through the estuary, which is given by the river discharge rate ($R$).

$$t_F = \frac{V_F}{R}$$

In practical application, flushing time according to Equation 1 is difficult to determine without extensive measurements of freshwater inflows and the salinity structure of an estuary. Using numerical modeling technology, an estimate of flushing rate can be made by predicting the time it takes for a concentration of a numerical tracer to be reduced to a prescribed percentage of the initial concentration. In theoretical and practical studies of estuarine flushing rate, a reduction to 50% of the initial tracer concentration is often used as a measure of good flushing. In the IRL-Banana River study presented here, no optimal rate of flushing is prescribed. As long as the boundary conditions applied account for all major physical processes including freshwater inflows, tidal influence, non-tidal sea level variations, wind stress, and waves stresses where appropriate, a model simulation will approximate the actual flushing rate.
Figure 10 shows the entire model domain in which tracer concentration values dropped to 50% or less in all areas south of the Melbourne Bridge. Tracer concentration values of 10 ppt or less were reached in about 150 days in areas south of the Melbourne Bridge. All areas north of the bridge remained at concentrations of about 11ppt or higher through the simulation, thus exceeding the 50% reduction threshold for flushing. In terms of flushing, areas from about the Eau Gallie Bridge and south benefited from freshwater inflows from Eau Gallie River, Crane Creek, Turkey Creek and the Sebastian River IRL Tributaries.

Figure 9. Predicted tracer concentration for Model Run 1, existing configuration after 340 days of simulation. Tracer units are parts per thousand (ppt).
Figure 10. Predicted tracer concentration over the entire model domain for Run 1, existing configuration after 340 days of simulation. Tracer units are parts per thousand (ppt).

The lowest concentration values that can be extracted from the model results in the north Banana River and the adjacent IRL compartment, range from about 16.8 to over 19 parts per thousand (ppt) or about 85 % or more of the original concentration value. Given the approximate definition of estuarine flushing the dye concentrations plotted in Figure 11 indicate that compartments shown in Figure 7 have not been flushed to the 50% level. However, a comparison of the time series of numerical dye concentration at Stations 1 through 5 shows a decline of about 1 to 3 parts per thousand (ppt) depending on location. The smallest predicted decline occurred at Station 3 in the compartment to the north of SR 528 (see Figure 7) where the
concentrations dropped by about 4% to about 19.2 ppt. Larger predicted declines in tracer concentration occurred at Stations 1 and 4 where concentrations decreased by about 14% to 15% to about 17 ppt. Station 1 is located in the compartment just to the south of the SR 520 causeway crossing the Banana River (Figure 7) and Station 4 is located in the IRL just to the south of the SR 520 causeway. The tracer concentration records shown in Figure 11 are the basis of comparison with predicted tracer concentrations associated with Model Runs 2 through 9 listed in Table 1.

![Image: Tracer Concentrations: Existing Conditions]

Figure 11. Prediction of tracer concentration time series at numerical monitoring stations shown in Figure 7. Predictions are from Model Run 1, the existing configuration, under model boundary conditions of 2015.

**6.2 Model Run 2: 528 Bridge Span**

The configuration of Model Run 2 includes a wide bridge span across the Banana River on SR 528 as shown in Figure 12. All other model components remain the same as in the existing case. The span is approximately 4,500 feet long as represented in the model grid. Figure 13 shows tracer concentrations in the north compartments of the Banana River and adjacent IRL after 340 days of model simulation. Tracer concentration in compartments north of SR 520 remained above 16 ppt and were only fractionally lower in the Banana River. compartments north of SR 528. Tracer concentrations in the remainder of the IRL included in the model were nearly identical or identical to tracer concentrations predicted for the exiting case of Model Run 1.
Figure 12. SR 528 bridge span across the Banana River specified in Model Run 2. Bridge span is approximately 4,500 feet long.

Figure 13. Predicted tracer concentration for Run 2, 528 single bridge span, after 340 days of simulation. Tracer units are parts per thousand (ppt).
Figure 14 compares the predicted time series of tracer concentrations at numerical monitoring Station 2, for the existing configuration with the model results based on the SR 528 bridge span. Station 2 is located in the Banana River compartment between SR 520 and 528 (see Figure 7). At the end of the model run, the predicted reduction in tracer concentration with the bridge span in place is 0.1 ppt. In the compartment to the north of the bridge span (Station 3), model predictions with and without the bridge span are virtually identical as shown in Figure 15.

Figure 14. Tracer concentration predicted by Model Runs 1 and 2 at Station 2. Location is shown in Figure 7.

The dividing line between IRL compartments having concentrations below and above 10 ppt marking the 50% reduction level, remained at the Melbourne causeway-bridge structure. South the Melbourne Bridge, tracer concentrations reached and maintained the 50% reduction level after about 150 days. (see Figure 10).
6.3 Model Run 3: 528 and 520 Bridge Spans

Model Run 3 includes span bridges on both SR 528 and SR 520 across the Banana River as shown in Figure 16. The spans are 4,500 feet on SR 528 and 6,500 feet on SR 520. Figure 17 shows tracer concentrations in the north compartments of the Banana River and adjacent IRL after 340 days of model simulation. As in Model Run 2, tracer concentration in compartments north of SR 520 remained above 18 ppt and were fractionally lower in the Banana River compartment to the south of SR 520. However, compared to Model Run 2 including only the SR 528 bridge span, the combination of bridge spans on both SR 528 and SR 520, produced a notable reduction of tracer concentrations at both Station 2 and Station 3 as shown in Figure 18 and Figure 19.

Figure 16. Tracer concentration predicted by Model Runs 1 and 2 at Station 3. Location is shown in Figure 7.
Figure 16. SR 528 and SR 520 bridge spans across the Banana River specified in Model Run 3. The SR 528 span is approximately 4,500 feet long and the SR 520 span is about 6,600 feet long.

Figure 17. Predicted tracer concentration for Run 3, 528 and 520 Bridge Spans after 340 days of simulation under Model Run 3. Tracer units are parts per thousand (ppt).
Model Run 3 results indicate a distinctive improvement in flushing as seen in Figure 18, which compares Model Runs 1 to 3 at Station 2. Numerical monitoring Station 2 is located in the Banana River compartment between the SR 528 and SR 520 bridge spans. The minimum tracer concentration found in Model Run 3 is about 16.6 ppt or about a 17% decline to about 83% of the initial values with both bridge spans in place. This compares to about an 8% decline to 92% of the initial values for the single SR 528 bridge span. The predicted decrease in tracer concentration under Model Run 1 for the existing causeway configuration is 7.5%. In the compartment to the north of SR 528, model predictions indicate an improved flushing when both the SR 528 and SR 520 spans are in place as shown in Figure 19. Maximum predicted decrease in tracer concentration was 9% down to about 90% of the initial value, compared to a decrease of about 4% to 96% of the initial value predicted by Model Runs 1 and 2.

Model results over the main body of the IRL were similar to those of Model Run 1 and Model Run 2. Freshwater inflows from the tributaries of the central IRL, along with exchanges with the coastal ocean though Sebastian Inlet produced a 50% reduction in dye concentration by about day 150 of Model Run 3. The progression of dye concentration and drogue movement can be viewed in the animations provided in the electronic appendix.

Figure 18. Tracer concentration predicted by Model Runs 1, 2, and 3 at Station 2. Location is shown in Figure 7.
6.4 Model Run 4: 528 and 520 Four Bridge Spans

Model Run 4 is termed the “4-span” case and includes a total of four bridge spans across the IRL and Banana River as shown in Figure 20. SR 528 bridge spans across the IRL and Banana River are 4,800 and 4,500 feet long, respectively. The SR 520 spans are approximately 3,800 and 6,500 feet. Along SR 528, the spans are 4,800 feet long across the IRL and 4,500 feet long across the Banana River. The SR 520 spans are 3,800 feet across the IRL and 6,500 long across the Banana River.
The overall results of the model tests are similar to those of Model Run 3, which included only the Banana River Spans. Figure 21 shows the details of tracer concentration in northern compartments of the model domain. A visual time series of tracer distribution over the entire model grid and in the north compartments can been seen in the animations provided in the electronic appendix. Figure 22 shows a time series of tracer concentration predicted at Station 3, which is in the Banana River compartment between SR 528 and 520. Model 4 results at this station are nearly identical to those of Model Run 3 for this compartment. The minimum tracer concentration is about 16.6 ppt or about a 17% decline to about 83% of the initial values with both bridge spans in place. North of SR 528, Model Run 4 results are the same as the Model Run 3 results as shown in Figure 19. The presence of both the SR 520 and SR 528 spans results in predicted decrease in tracer concentration was 9% down about 90% of the initial value compared to a decrease of about 4% to 96% of the initial value predicted by Model Runs 1 and 2.

![Figure 21. Predicted tracer concentration for Run 4, 528 and 520 Bridge Spans across the IRL and Banana River after 340 days of simulation. Tracer units are parts per thousand (ppt).](image)

The four-bridge span modification of Model Run 4 also includes spans across the IRL at SR 520 and SR 528. Figure 23 shows Model Run 4 results at Station 4 in the IRL compartment between the spans. Here, tracer concentrations dropped to a minimum of about 17.5% to about 16.5 ppt, which is 82.5% of the initial 20 ppt. This compared to tracer concentration declines of 14% under the existing configuration of Model Run 1. It is noted that this IRL compartment is
better flushed compared to the equivalent Banana River compartment to the east where tracer
centrage concentration declines are about 4% under the existing conditions of Model Run 1.

Figure 22. Tracer concentration predicted by Model Runs 1, 2, 3, and 4 at Station 2. Location is shown in Figure 7.

Figure 23. Tracer concentration predicted by Model Runs 1 and 4 at Station 2. Location is shown in Figure 7.
6.5 Model Run 5: 528 Double Span

Two separate SR 528 spans are included in Model Run 5 (Figure 24). Location of two SR 528 bridge spans across the Banana River. The west span is 1000 feet long and the east span is 1150 feet. Results of this model run are similar to the existing case of Model Run 1 and to all other cases in that only marginal improvement in the flushing is predicted. The tracer concentration values in the north Banana River compartments remains above 18 ppt at the end of the simulation (Figure 25).

![Figure 24](image1.png)

Figure 24. Location of two SR 528 bridge spans across the Banana River. The west span is 1000 feet long and the east span is 1150 feet.

![Figure 25](image2.png)

Figure 25. Predicted tracer concentration for Model Run 5, SR 528 double span across Banana River after 340 days of simulation. Tracer units are parts per thousand (ppt).
Figure 26 compares predicted tracer concentrations at Station 3 in the Banana River north of SR 528 for the SR 528 double span configuration of model case 5, whereas Figure 27 shows predicted concentrations at Station 2 in the Banana River compartment between SR 528 and SR 520 for the same model test. At both locations, reduction in tracer concentrations are on the order of 4% to 8% and the difference compared to the model test of the existing configuration is a less than 1 ppt.

Figure 26. Tracer concentration predicted by Model Runs 1 and 5 at Station 3. Location is shown in Figure 7.

Figure 27. Tracer concentration predicted by Model Runs 1 and 5 at Station 2. Location is shown in Figure 7.
In the overall model grid, tracer values drop below 10 ppt level marking the 50% flushing threshold after about 150 days in the IRL compartments south of the Melbourne Causeway and bridge structure, where flushing benefits from exchanges through Sebastian Inlet and freshwater inflows.

6.6 Model Run 6: SR 528 and SR 520 Double Bridge Spans

In the Model Run 6, double span bridges are specified for the SR 528 and SR 520 segments that cross the Banana River (Figure 28). The SR 528 spans are 1000 and 1150 feet long across Banana River, respectively. The SR 520 spans are 1,650 and 1,400 feet long. Results for this model case were similar to all other test cases indicating only a fractional improvement in flushing. After 340 days of simulation, tracer values in all north IRL and north Banana River compartments are 85% or more of the initial 20 ppt value at 18 ppt or more (Figure 29).

Figure 28. Location of double SR 528 and SR 520 bridge spans across the Banana River. The west 528 span is 1000 feet long and the east 528 span is 1150 feet. The west SR 520 span in 1650 feet long and the east 520 span is 1400 feet long.
Figure 29. Predicted tracer concentration for Run 5, SR 528 and SR 520 double spans across Banana River after 340 days of simulation. Tracer units are parts per thousand (ppt).

Figure 30 compares Model Run 1 based on the existing configuration, with the double span Model Runs 5 and 6 at Station 2 in the Banana River compartment between SR 528 and SR 520. At Station 2, tracer concentrations are reduced by about 10% to about 90% of the initial values for all three cases shown in Figure 30. Tracer concentrations under both double span cases remain within 1 ppt of tracer concentrations predicted for the existing configuration of the SR 528 and SR 520 structures. At Station 3 in the Banana River to the north of SR 528, predicted tracer concentrations drop by about 0.75 ppt over the course of the model runs for all three cases and remain at about 96% of the initial value of 20 ppt (Figure 31). Thus, in comparison with the longer single span structures tested under Model Runs 2, 3 and 4, the shorter double span bridge configurations provide less of a flushing benefit.
Figure 30. Tracer concentration predicted by Model Runs 1, 5, and 6 at Station 2. Location is shown in Figure 7.

Figure 31. Tracer concentration predicted by Model Runs 1, 5, and 6 at Station 3. Location is shown in Figure 7.
6.7 Model Runs 7 and 8: SR 528 and SR 520 Flow Relief Structures

The results of Model Runs 7 and 8 combined in this section were similar to other model tests. Predicted improvement in flushing is small but detectible. Figure 32 shows the location of the hypothetical flow relief structures placed in the SR 528 and SR 520 causeways. The length of the structures is approximated 160 feet as they cut across each causeway. Water depth in each of the structures is specified at about 8 feet.

Figure 33 compares the tracer concentrations that result from the existing configuration of Model Run 1 with the predicted tracer concentrations that result after 340 days from the flow relief structures specified in Model Runs 7 and 8. Tracer concentrations are fractionally lower in Model Runs 7 and 8 compared to the existing configuration, but still remain at about 85% or greater of the original concentrations at the beginning of each run. Animations of tracer concentrations and drogue movements predicted for Model Runs 7 and 8 can be found in the electronic appendix.
Figure 33. Predicted tracer concentration for Run 1 (A), existing configuration 9, Model 7 (B) SR 528 flow relief structures, and Model Run 8 (C) SR 528 and SR 520 flow relief structures. Tracer concentration units are parts per thousand (ppt).

Figure 34 compares the progress of tracer concentrations at Station 2 through the relief structure models runs. As stated above, the differences between the three model cases represented in Figure 33 are detectible but small. Compared to the existing confirmation represented by Model Run 1, the two model runs configured for relief structures resulted in reductions in tracer concentration of about 0.1 ppt based on the SR 528 relief structures and about a 0.2 to 0.3 ppt reduction in tracer concentration based on relief structures in both the SR 528 and SR 520. Thus, predicted concentrations are about 90% or more of the initial value of 20 ppt for all three cases. Model Run 8 based on relief structures in both causeways improved the flushing of this compartment by about 2%. Predicted tracer concentrations at Station 3 located in the Banana River compartment north of SR 528 are within 0.1 to 0.2 ppt among all three cases (Figure 35). Flushing action was improved by about 0.5% for the model run based on relief structures placed in both causeways.
Figure 34. Tracer concentration predicted by Model Runs 1, 7, and 8 at Station 2. Location is shown in Figure 7.

Figure 35. Tracer concentration predicted by Model Runs 1, 7, and 8 at Station 3. Location is shown in Figure 7.
6.8 Model Run 9: Banana River and Indian River Lagoon Flow Relief Structures

Model Run 9, termed “Relief 4”, is based on flow relief structures added to the SR 528 and SR 520 causeways crossing Indian River Lagoon as well as the Banana River as specified in Model Runs 7 and 8. Two additional flow structures were added to the SR 520 causeway compared to the Model Run 8 configuration. Figure 36 shows the positions of the structures placed in the model grid. The structures are approximately 160 feet wide and have depths set at about nine feet. Figure 37 shows the details of the predicted tracer concentration in the North Banana River and the IRL after 340 days of simulation.

![Image of SR 528 and SR 520 flow relief structures across the Banana River and the IRL associated with Model Run 9. Seven flow structures are located on the SR 520 Causeway in this case compared to the 5 structures specified in Model Run 8.](image-url)
Figure 37. Predicted tracer concentration for Model Run 9 including flow relief structures in SR 528 and SR 520 across the Banana River and IRL after 340 days of simulation. Tracer units are parts per thousand (ppt).

Figure 38 compares the results of Model Run 1, 8, and 9 at Station 2 located in the Banana River compartment between SR 528 and SR 520. The comparison is among the existing configuration, the relief structures of Model Run 8, and the configuration of Model Run 9 that includes 7 structures in the SR 528 causeway. Minimum tracer concentrations reached in Model Run 9 are about 18 ppt near the end of the 340-day simulation. This is a 10% reduction from the initial concentration to 90% of the initial value of 20 ppt. The maximum reduction in tracer concentration under the Model Run 8 configuration is about 9%.
Figure 38. Tracer concentration predicted by Model Runs 1, 8, and 9 at Station 2. Location is shown in Figure 7.

Figure 39 compares model results in the same Banana River compartment among the existing configuration, the SR 528 and SR 520 bridge spans of Model Run 3, and the relief structures of Model Run 9. The minimum tracer concentration of about 16.6 ppt is associated with the bridge span configurations of Model Run 3. This is about a 17% reduction to 83% of the initial tracer concentration compared to the 10% associated with the relief structure configuration of Model Run 9. In the IRL compartment, model results at Station 4 (Figure 40) show that the bridge spans over the IRL configured in Model Run 4, have an advantage over the relief structures of Model Run 9. Minimum tracer values in the IRL compartments reached about 16.4 ppt in the later part of Model Run 4. This represents about a 18% reduction in tracer concentration from the initial 20 ppt concentration value. This is compared to about a 13.5% reduction in tracer concentration under the existing configuration of Model Run 1 and the configuration of flow relief structures in the IRL under Model Run 9.
Figure 39. Tracer concentration predicted by Model Runs 1, 3, and 9 at Station 2. Location is shown in Figure 7.

Figure 40. Tracer concentration predicted by Model Runs 1, 4, and 9 at Station 4. Location is shown in Figure 7.
7.0 Conclusions

Numerical model experiments involving modification of the existing SR 528 and SR 520 causeway and bridge structures across the Banana River and the adjacent north compartment of the Indian River Lagoon indicate the potential for enhanced flushing benefits. The study results are summarized in Table 2, which compares the performance of each model configuration on the basis of the maximum percent reduction in tracer concentration from the initial 20 ppt during each model run. Table 3 provides the net difference in tracer concentration between the results of the Model Run 1 existing configuration and each of the other model cases. The percentages are based on data extracted from the numerical monitoring stations shown in Figure 7 of this report.

The model tests indicate that modification of the SR 528 and SR 520 causeway and bridge structures would likely provide flushing benefits on the order of a 10% improvement in selected cases. Long bridge spans across the Banana River on both SR 528 and 520 (Model Run 3) are predicted to improve flushing action by 9.3% (Table 3). The flushing benefit extends north of SR 528 to the compartment containing numerical monitoring Station 4 where the improvement is predicted to be 5.3%. A fundamental conclusion of this study is that significant improvement in flushing of the Banana River north compartments and the adjacent IRL compartments would require bridge spans on SR 520, as well as SR 528.

Table 2. Percent reduction in tracer concentration. Most favorable cases are listed in bold.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>Description</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
<th>Station 5</th>
<th>Model Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Existing Configuration</td>
<td>15.6%</td>
<td>7.7%</td>
<td>4.1%</td>
<td>14.3%</td>
<td>8.8%</td>
<td>10.1%</td>
</tr>
<tr>
<td>2</td>
<td>528 Bridge Span</td>
<td>16.1%</td>
<td>8.0%</td>
<td>4.2%</td>
<td>14.3%</td>
<td>8.8%</td>
<td>10.3%</td>
</tr>
<tr>
<td>3</td>
<td><strong>528 and 520 Bridge Spans</strong></td>
<td><strong>17.4%</strong></td>
<td><strong>17.0%</strong></td>
<td><strong>9.4%</strong></td>
<td><strong>14.3%</strong></td>
<td><strong>8.8%</strong></td>
<td><strong>13.4%</strong></td>
</tr>
<tr>
<td>4</td>
<td><strong>528 and 520 Four Bridge Spans</strong></td>
<td><strong>17.4%</strong></td>
<td><strong>17.0%</strong></td>
<td><strong>9.4%</strong></td>
<td><strong>17.9%</strong></td>
<td><strong>10.8%</strong></td>
<td><strong>14.5%</strong></td>
</tr>
<tr>
<td>5</td>
<td>528 Double Spans</td>
<td>15.6%</td>
<td>8.0%</td>
<td>4.1%</td>
<td>14.3%</td>
<td>8.8%</td>
<td>10.2%</td>
</tr>
<tr>
<td>6</td>
<td>528 and 520 Double Spans</td>
<td>15.6%</td>
<td>9.4%</td>
<td>4.4%</td>
<td>14.3%</td>
<td>8.8%</td>
<td>10.5%</td>
</tr>
<tr>
<td>7</td>
<td>528 Flow Relief Structures</td>
<td>15.6%</td>
<td>7.7%</td>
<td>4.1%</td>
<td>14.3%</td>
<td>8.8%</td>
<td>10.1%</td>
</tr>
<tr>
<td>8</td>
<td>528 and 520 Flow Relief Structures</td>
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<td>7.7%</td>
<td>4.1%</td>
<td>14.3%</td>
<td>8.8%</td>
<td>10.1%</td>
</tr>
<tr>
<td>9</td>
<td><strong>528 and 520 Flow Relief Structures: IRL and Banana River</strong></td>
<td><strong>16.2%</strong></td>
<td><strong>10.3%</strong></td>
<td><strong>4.4%</strong></td>
<td><strong>15.4%</strong></td>
<td><strong>9.5%</strong></td>
<td><strong>11.2%</strong></td>
</tr>
</tbody>
</table>

It is noted that a SR 528 bridge span alone (Model Run 2) is predicted to provide almost no flushing benefits. However, when combined with a bridge span included in Banana River section of SR 520, the flushing benefit is substantially improved. Model Run 4 extends the predicted benefits of bridge spans to the IRL, including bridge spans across the both the IRL and Banana River. In this case a modest improvement in flushing is predicted for the IRL compartment between SR 520 and SR 528, as well as in the compartment north of SR 528. The improvement of flushing action in the IRL is measured against the existing case of Model Run 1. It is noted that this section of the IRL has better flushing action as presently configured compared to the Banana River compartments directly to the east as quantified in Table 2.
Table 3. Percent reduction in tracer concentration compared to the existing configuration of Model Run 1. Most favorable cases are listed in bold.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>Description</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
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<td>Existing Configuration</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>528 Bridge Span</td>
<td>0.5%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.2%</td>
</tr>
<tr>
<td>3</td>
<td>528 and 520 Bridge Spans</td>
<td>1.8%</td>
<td>9.3%</td>
<td>5.3%</td>
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<td>0.0%</td>
<td>3.3%</td>
</tr>
<tr>
<td>4</td>
<td>528 and 520 Four Bridge Spans</td>
<td>1.8%</td>
<td>9.3%</td>
<td>5.3%</td>
<td>3.6%</td>
<td>2.0%</td>
<td>4.4%</td>
</tr>
<tr>
<td>5</td>
<td>528 Double Spans</td>
<td>0.0%</td>
<td>0.3%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
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<td>0.0%</td>
<td>1.7%</td>
<td>0.3%</td>
<td>0.0%</td>
<td>0.0%</td>
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<td>7</td>
<td>528 Flow Relief Structures</td>
<td>0.0%</td>
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<td>2.6%</td>
<td>0.3%</td>
<td>1.1%</td>
<td>0.7%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

The flow relief structures on Model Runs 7 and 8 were not predicted to have a detectible impact on flushing of the IRL and Banana River compartments. However, marginal improvement in flushing action was a predicted by Model Case 9, which included 7 additional flow relief structures embedded in the SR 520 causeway in combination with 3 additional relief structures on the SR 528 causeway.

The present study, based on a calibrated model that includes all the physical processes that produce circulation, demonstrates that modifications of the SR 528 and SR 520 structures to include substantial bridge spans can improve the flushing of the compartments of the Banana and IRL that are bounded by these structures. Such improvements are on the order of about 10% better than the present level of flushing over the same time period.

The results of this study are not intended to be at the design level, but are calibrated to the degree that can be considered accurate within the limits of the modeling technology and data used to drive and calibrate the CMS model. A design level modeling effort should be accomplished with a three-dimensional model such as the Environmental Fluid Dynamics Code (EFDC) that is now being applied to test the benefits of other options to improve water quality (Zarillo and Listopad, 2017). A fully 3D coupled hydrodynamic and water quality model at high spatial resolution would provide additional information about potential influence of causeway modifications or other anthropogenic alterations to the IRL system on the salinity regime, water quality, and water levels.
8.0 References


