Preliminary Study of the Effects of Causeway Removals in the IRL

by

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Executive Summary

The impacts of causeways on seagrass in the Indian and Banana River Lagoons have been debated for many years. The recent development of a hydrodynamic and water quality model for the Lagoon allowed for simulation of causeway removals, and predicted the impacts of their removals on seagrasses. The model domain included the area between Ponce de Leon Inlet and the St. Lucie Inlet, while the model results were evaluated for the causeways between Haulover Canal and Wabasso. Different scenarios were evaluated, including full and partial causeway removals and watershed flow reductions were simulated to test the sensitivity of the model. Model results in the form of changes in surface velocity, flushing, flow volume, salinity, total suspended solids and incident light, were analyzed. The model accuracy, as determined by the model developer, was used to compare results. It is concluded that neither full nor partial removal of causeways will significantly benefit seagrass distribution in the Indian or Banana River Lagoons. In fact, negative impacts may be caused as a result of causeway removals. Previous modeling studies in the Indian River Lagoon (Evink, 1980) and Laguna Madre, TX (Powell et al., 1997) found similar results.

The US Army Corps of Engineers will be working with a fine scale finite element model to see if the addition of culverts or relief spans in the causeways (on scales smaller than allowed by this model grid) would be beneficial to water quality in the lagoon.

Background

One of the many possible management strategies for the Indian River Lagoon (IRL) discussed among resource managers, scientists, and the interested public is the complete or partial removal of causeway-bridge fill material (USACE and SJRWMD, 2002; IRL National Estuary Program, 1996; IRL Field Committee, 1987; Evink, 1980). The rationale for such a strategy is that causeways restrict or alter the circulation of Lagoon waters, which may increase pollutant load residence times, adversely impacting water quality and seagrasses. This rationale seems plausible when one considers the fact that there are 17 causeways within the Indian River and Banana River lagoons, from Haulover Canal to the St. Lucie Inlet (Figure 1 and Table 1).

The Indian River Lagoon is a shallow, well-mixed estuary (Sheng and Davis, 2003). Circulation and flushing throughout much of the IRL is quite limited as the term “lagoon” characteristically implies. It is an estuarine lagoon because its basin has restricted hydraulic communication with the ocean, it exhibits microtidal amplitudes in water elevation (Smith, 1987), its circulation and flushing is largely wind-driven, and residence times are relatively long – on the order of months to over a year for nearly complete water exchange in most of the northern and central segments of the IRL (Steward et al, 2003; Sheng, 1997; Smith, 1993; Evink, 1980). Smith(1987) found that in the portion of the IRL north of Sebastian Inlet, 92% to 99% of water level variations are caused by non-tidal, low-frequency constituents. The current causeways are transparent to these low frequency oscillations. So, the question is: *do causeways substantially augment residence times of incoming pollutant loads,* *decrease water quality and, consequently, degrade the seagrass resource?* Or, alternatively stated, *will removal of one or more causeways substantially improve water quality and the potential for meeting seagrass restoration targets?*

A partial answer to the latter question was attempted by Evink (1980) to address a concern of the Florida Department of Transportation that its design and construction of causeways may be environmentally deleterious. The study's findings and conclusions were based on results generated from a two-dimensional, finite-difference, circulation model (Ghioto, 1973). The study area included the Melbourne and Eau Gallie causeways (U.S.192 and S.R. 518, respectively, Figure 2). Evink examined the circulation results in conjunction with available water quality and biological data and came to the following deductions: "… the elevation records for the causeway and no causeway situations show slight lags and elevation differences. However, no significant differences are evidenced in these simulations… [And] the magnitude of water movement in relation to the volume of the basin and pollutant loading does not seem significant enough [with or without causeways] to alleviate water quality problem[s]."

Furthermore, the study concludes that circulation is more influenced by natural landforms (e.g. cuspate spits) and bathymetry than by the presence of causeways. The Eau Gallie and Melbourne causeways, as constructed, with relatively large central openings for the Atlantic Intracoastal Waterway (AIWW) and relief channels at their eastern and western ends, appear to allow considerable water movement throughout the study area. However, some compression of circulation and "delay [of water movement] is being experienced around relief structures."

The Evink study revealed much about IRL hydrodynamics, but the study did have its limitations and did not definitively answer the question about whether complete or partial causeway removal would, indeed, improve the environmental health of the IRL. Today, 23 years after the Evink study, we can take advantage of a recently developed three-dimensional model of the IRL – the Pollutant Load Reduction (PLR) Model (Sheng et al., 2003, Vol. I - IV) -- and preliminary water quality, salinity, and seagrass management targets (Steward et al., 2003) to conduct a more comprehensive re-evaluation of causeway removal.

Other Studies

Nielsen et al. (2000) examined GIS seagrass maps for the IRL from 1943 and 1992 and did not notice a loss of seagrass over that time due to hardened structures along causeways. They did note a small amount of seagrass growth along both Pineda and Merritt Island causeways due to shallower than historical depths.

Powell et al. (1997) used a fine grid, two-dimensional, finite element model to study the removal of JFK causeway in Laguna Madre, TX. Their study found only minimal changes in flow and salinity when the causeway was removed from the model. Flow increased by only 4% and salinity increased by 0.9 ppt during a dry period and only 0.4 ppt during a wet period.

Purpose and Scope

The purpose of this study is to conduct a preliminary, large scale evaluation of the removal of 16 of the 17 causeways in the Indian River and Banana River lagoons (Table 1; the Seaway Bridge Causeway in Ft. Pierce is not included in this study because substantial facilities and infrastructure are built on the causeway and removal would not be feasible). The evaluations tested the hypothesis that the full or partial removal of one or more causeways will cause a beneficial response in the Lagoon system over a one-year period, as represented by the following environmental variables:

- Salinity
- Velocity and flow
- Total suspended solids (TSS) concentrations, and
- Solar light penetration at depth (or % incident light).

This evaluation assesses causeway removal as a management strategy to meet the following goal and objectives of the IRL-N Feasibility Study:

> *Goal* -- Improve Ecological Values
> *Objectives* -- Improve water quality in the Lagoon, and increase spatial extent and functional quality of seagrass.

This study consisted of comparisons of PLR Model simulation runs for a number of different scenarios. The first step was to run a base case, then run five sets of model scenarios and compare results between the base case and the modification scenarios (2-6).

1. All causeways included (base case)
2. All causeways included with:
    a. 100% runoff from the watershed
    b. 0% runoff from the watershed
    c. 50% runoff from Turkey Creek to roughly approximate the effects of operating the proposed C-1 Rediversion Project
3. All causeways are removed,
4. Each causeway is removed individually (while the others remain),
5. A select group of causeways is removed, and
6. Partial removal of a selected causeway

Any differences in Lagoon response to causeway removals relative to the base case were examined as to significance and potential benefit.

If any of the series of causeway removal simulations indicated a significant improvement over the base case to any segment of the IRL, then the potential relative benefit to a performance measure, particularly salinity, TSS, or percent incident light, will be determined.

Potential benefit or harm is defined as the occurrence of a difference between the removal and base case scenarios that is greater than the model error for the variable tested (salinity, TSS, etc.). The approach used to determine these differences was to quantify the annual mean and standard deviation of the largest spatial or single cell difference between scenarios. This maximum difference was used as the indicator of potential benefit or adverse impact. Single time step, or hourly, results were also presented in some cases to indicate short-term temporal extremes between scenarios.

If the model results indicate that removal of any one or more causeways could provide benefit and the results reach an acceptable approximation of a performance measure, then more detailed evaluation of causeway removal is warranted. Of course, this additional evaluation is not necessary if there is no discernable difference between the with-causeway and without-causeway results or if the without-causeway results indicate an adverse impact to the IRL.

The Study Area and Model Representation

The selected study area for this evaluation is the Banana River Lagoon and the IRL from Haulover Canal to Wabasso Causeway (Figure 1). Model runs that simulated physical changes and water quality were conducted by running the PLR (CH3D-IMS) water quality model for 1998 conditions for the model domain between Ponce de Leon Inlet and St. Lucie Inlet. The model was run over this domain in order to take advantage of available boundary conditions, and output was generated for the study area. While it is often necessary to run models for several years to capture climatic variations, the conditions during 1998 included both extreme wet and dry conditions including a sharp transition from El Niño conditions to La Niña conditions. The El Niño conditions were characterized by a shift of the winter storm track into the southern states, which resulted in an exceptionally wet winter, while the La Niña conditions resulted in an unusually dry summer. Relatively average rainfall occurred only in the fall of 1998.

Table 1. Causeways in the Indian River Lagoon and Banana River Lagoon

#	NAME	HIGHWAY	NEAREST MUNICIPALITY
	INDIAN RIVER LAGOON		
1	Railroad Bridge		
2	Brewer Memorial Parkway	SR 406	Titusville
3	NASA Causeway West	SR 405	North of Bellwood
4	Bennett Causeway West	US A1A, SR 528	Indianola
5	Merritt Is. Causeway West (Hubert Humphrey Bridge)	SR 520	
6	Pineda Causeway West	SR 404	Viera
7	Eau Gallie Causeway	SR 518	Melbourne, (Eau Gallie)
8	Melbourne Causeway	US 192, SR500	Melbourne, Indialantic
9	Wabasso Causeway	SR 510	Orchid
10	North Beach Causeway	US A1A	Ft. Pierce
*	Seaway Bridge Causeway	US A1A	Ft. Pierce
11	Hutchinson Is. Causeway	SR 732	Jensen beach
12	St. Lucie Causeway	US A1A	Stuart
	BANANA RIVER LAGOON		
13	NASA Causeway East	SR 405	Canaveral
14	Bennett Causeway East	US A1A, SR 528	Canaveral
15	Merritt Is. Causeway East (Hubert Humphrey Bridge)	SR 520	Canaveral / Cocoa Beach
16	Pineda Causeway East	SR 404	Satellite Beach

* The Seaway Bridge Causeway in Ft. Pierce is not included in this study because facilities and substantial infrastructure are built on the causeway and removal would not be feasible.

Figure 2 shows the locations of the CH3D-IMS model grid, IRL inlets, the eight segments analyzed for flushing characteristics by the University of Florida, causeways, major tributaries, and a few other key features. The IRL causeways, as numbered for this study, are listed above in Table 1.

Causeway locations are approximated in the model grid by the insertion of flow barriers on the faces of the cells closest to the actual causeway locations. As shown in Figure 3, with heavy red lines, flow barriers approximate the parts of the causeway that impede flow.

Salinity and velocity values were saved at 56 locations over the entire study area every hour during each one-year simulation. These 56 locations were selected to reflect changing conditions near the causeways. Four model grid cells were assigned for the NW, NE, SW, and SE sides of the causeways in the IRL (12 causeways requiring 48 cells) and two cells were assigned on the North and South sides of each of the Banana River Lagoon causeways (4 causeways, 8 cells, Figure 3). Monthly mean TSS and Percent Incident Light at the Bottom (PILB) were saved in every cell for plotting on the model grid, while flow was saved in the transects bracketing causeways 6, 7, and 8 (Figure 3).

To further evaluate the difference between scenarios, the maximum salinity and velocity values in the year-long, one hour time series in the 56 locations, along with their standard deviation for the year, were determined. These additional statistics are occasionally cited in this report, where short-term ranges of variables are of interest.

The Base Case and Model Performance with Tributary Discharge Reductions

A series of three simulations were run initially to test the overall performance of the CH3D-IMS water quality model, as delivered from the University of Florida with the same boundary condition files, with all causeways in place and all major tributaries discharging.

The objective of the first simulation, or the "base case," was to save the bottom salinity in the 56 selected cells at every hour for comparison with salinities from the other scenarios. Salinity was selected as the preliminary evaluation parameter because it is conservative, is easy to monitor, and it is critical to the success of the performance standard, i.e., seagrass growth and survival. It can also reflect conditions of improved circulation at the bottom of the water column, where seagrasses are rooted.

The University of Florida conducted a sampling program at five monitoring stations in the study area. Comparisons of modeled salinity with the observed data reflected an annual mean difference of 2.7 ppt at the surface and 1.8 ppt at the bottom. The evaluations of the effect of causeway removals were first based on comparisons of the maximum annual mean changes in salinity between the base case and the various scenarios. Differences in salinity that are greater than model error for the bottom salinity (1.8 ppt) are judged to be significant, while differences below the model accuracy are considered insignificant.

In the base case the annual mean salinity ranged between the study sites from 16.6 ± 1.5 ppt south of NASA Causeway East (#13) to 29.2 ± 3.6 ppt just north of Wabasso Causeway (#9). The maximum modeled salinity was 36.3 ppt, which occurred on July 6 on the NE side of Wabasso Causeway during extremely dry conditions. The minimum modeled salinity, 11.1 ppt, occurred on March 29 on the SW side of Melbourne Causeway (#8) immediately following the wet El Niño winter.

The second simulation scenario involved reducing all tributary discharges to zero, with all of the causeways in the model, to test the response of the model. The model performs as expected by showing an increase in salinity throughout the IRL. The greatest annual mean increase for the year for this case was 9.1 ppt on the SE side of Melbourne Causeway. This reflects the elimination of flow from Turkey and Crane Creeks (1.5 m^3/s annual mean flow), both of which discharge to the IRL just south of Melbourne Causeway. The smallest annual mean increase in salinity in the study area is 2.3 ppt on the north side of NASA Causeway East (#13), the northernmost causeway in Banana River Lagoon, which does not receive appreciable surface discharges.

An additional run under the second simulation scenario involved reducing Turkey Creek (C1) discharges by 50%, while maintaining all other discharges, to simulate the expected effect of the C-1 Rediversion project. The largest annual mean salinity increase (2.2 ppt) was experienced at the SE side of Melbourne Causeway, which is the closest causeway to Turkey Creek, a major tributary inflow that includes the C-1 basin. (It should be noted that the mean monthly salinity at this site increased between 2.6 and 3.7 ppt for the months August to December, resulting in salinity being restored above 20 ppt, which is a goal of the C-1 Rediversion Project.)

These performance tests, using elimination and partial reduction of tributary discharges without any changes in causeways, demonstrate that the CH3D-IMS model reasonably represents salinity changes in the IRL.

Changes in Salinity for Various Scenarios

The effects of removal of all causeways simultaneously (scenario 3), removal of one causeway at a time (scenario 4), and removal of causeways 6, 7, and 8 together (scenario 5), are described in this section. In these selective causeway removal tests, salinity was once again chosen as the parameter of interest, with results again presented for the bottom layer of the model grid since the impacts at the bottom of the water column would have the greatest effect on seagrass growth.

When all causeways are removed together (scenario 3), the largest modeled increase in annual mean bottom salinity for the examined sites is 0.6 ppt, occurring at the SE side of NASA Causeway West (#3). The greatest increase in salinity from the base case for one hour records in the year-long time series is 2.6 ppt at the NE side of Melbourne Causeway, the first causeway north of Sebastian Inlet. The greatest decrease in salinity from the base case for one hour records in the year-long time series is –2.5 ppt at the NE side of Wabasso Causeway, just to the south of the inlet. With a model accuracy of 1.8 ppt for annual average bottom salinity, it may be concluded that there is not a significant effect on salinity caused by simultaneous removal of all causeways.

When each causeway is removed separately (scenario 4), the maximum annual mean salinity does not change more than 0.4 ± 0.2 ppt in any cell. The removal of NASA Causeway West causes the greatest increase in salinity from the base case in the hourly time series, 2.1 ppt. The greatest decrease in salinity from the base case in the hourly time series is –2.6 ppt, occurring at the NW side of Melbourne Causeway when this causeway is removed. For each causeway removed, the maximum increase and decrease typically occur in the cells closest to the causeway. As with the previous scenario, no significant effects on salinity are caused by the removal of any one causeway.

At this point in the study, it was determined that removal of a select set of causeways may prove to be beneficial. The group of causeways selected for this evaluation included the Pineda Causeway (#6) spanning the Indian River (SR 404), the Eau Gallie Causeway (#7, SR 518), and the Melbourne Causeway (#8, US 192, SR 500). The area between and immediately surrounding these causeways exhibit some of the worst water quality and seagrass coverage in the Lagoon system (Steward et. al., 2003). It was anticipated that a strategy that would effectively improve flushing and salt transport in this area might yield an acceptable benefit/cost result.

When Pineda, Eau Gallie, and Melbourne Causeways (6, 7 & 8) are removed together, the resulting annual mean salinity difference did not exceed 0.1 ppt for any location. The greatest increase in bottom salinities from the one hour time series is 2.0 ppt at the NE side of Melbourne Causeway (this location experienced an annual mean salinity difference of 0.1 ± 0.4 ppt). The greatest decrease in one hour is –2.4 ppt on the NW side of Melbourne Causeway (which experiences an annual mean salinity difference of 0.02 ± 0.3 ppt for this case). Thus, no significant effects on salinity are anticipated with the cumulative removal of causeways 6, 7, and 8.

To further evaluate this option, flows were reduced from the tributaries and the model was rerun. When Causeways 6, 7, and 8 are removed together, and the discharge from C-1 or Turkey Creek is reduced by 50%, the greatest changes in modeled bottom salinity occur around those three causeways. In this case the SE and SW cells at Melbourne Causeway experience the greatest increase, 2.2 ppt, in modeled annual mean salinities. The SE location at Melbourne Causeway has the largest increase in salinity, 5.6 ppt, during one hour. This location also has the greatest decrease, -1.4 ppt, during one hour records in the time series. Thus, the conclusion was reinforced that no significant local effects on salinity are caused by removal of causeways 6, 7, and 8. The changes in these runs are consistent with the reduced flow runs under the base case scenario.

Velocity Verification for Removal of Causeways 6, 7 and 8

To further assess the removal of the three causeways, 6, 7, and 8, velocity and flow output from the model was evaluated. The CH3D-IMS model computes velocity in four layers. The surface layer flow generally follows the direction of the wind, while the lower layers may flow in any direction to maintain balance and continuity. Figure 4 shows a sequence of vertical velocity profiles over a period of five hours at Brewer Causeway (#2). As can be observed, lower layers can change direction due to factors other than wind.

Surface longitudinal velocities were examined since it is assumed that removal of causeways will have the greatest numerical effect on the relatively larger velocities in this layer. If changes are not significant in the surface layer, then it may be assumed that changes in bottom velocities will also be insignificant. Southerly velocities and flows are reported as positive in this model, while northerly values are negative. The southerly velocities were saved separately from the northerly velocities so that the means of the southerly and the northerly velocities could be separately calculated for each of the four cells located near each of the removed causeways. The main channels for the three causeways are represented by the NW and SW cells, while the near shore areas are represented by the NE and SE cells.

With all causeways included in the model, i.e., the base case, the SW cell near Pineda Causeway (#6) showed the greatest annual mean velocities, 5.2 cm/s northward and 5.7 cm/s southward. The SE cell showed an annual mean northward velocity of 4.3 cm/s and southward velocity of 3.2 cm/s. When the three causeways were removed, the annual mean northward and southward velocities were reduced to 4.4 and 4.5 cm/s, respectively, at the SW cell and increased to 4.7 and 4.0 cm/s, respectively, at the SE cell. When a causeway is removed, the flow that had been channeled through the causeway opening would be expected to disperse across the lagoon, which would result in lower velocities in the channel or west cells and higher velocities in the near shore or east cells.

Further investigation of separate northerly and southerly flow data showed that the annual mean northerly velocities decreased in all six channel cells, while the annual mean southerly velocities decreased in all the SW channel cells but increased in all the NW channel cells. We believe that this is due to wind , and represents circulatory secondary currents or eddies that are removed when causeways are eliminated. A similar finding was also observed by the University of Florida (Sheng, 2003).

The maximum decrease in annual mean southerly velocities in the SW channel cells was 1.2 cm/s at Melbourne Causeway (#8). The largest change in annual mean northerly velocity was an increase of 1.2 cm/s, at the NE side of Melbourne Causeway. The largest change in maximum1-hour southerly velocity from modeled time series records was 3.7 cm/s at the SE side of Pineda Causeway, while the largest change in maximum 1-hour northerly velocity from the modeled time series records was an increase of 4.1 cm/s at the NE side of Melbourne Causeway.

Flow Volume Verification for Removal of Causeways 6, 7 and 8

For the evaluation of flow volume passing through the causeway areas, seven transects (labeled A through G) are defined as “flow transects” near causeways 6, 7 & 8 (Figure 5). Transect A is near the mouth of Banana River Lagoon to detect any change in the flow to or from that waterbody. The remaining six transects are assigned in pairs, on both sides of, each of the 6, 7, and 8 causeways. One transect is directly adjacent to the south side of a causeway, while the other is located a few cells north of the causeway. It is assumed that removing the causeways will have the greatest effect on longitudinal, as opposed to lateral, flow. As with the velocities, modeled positive flow is southerly and modeled negative flow is northerly. The model averages the flow volume over the entire water column and does not output values for each grid layer separately. This representation differs from that for the preceding velocity analysis.

With all causeways in the model, the annual mean southward flow varies from 126 m^3/s (Transect A) to 294 m^3/s (Transect E) while the annual mean northward flow respectively varies from 127 m^3/s to 295 m^3/s.

The difference in absolute values of longitudinal flow at each transect is small since northerly and southerly flows tend to balance each other. Transect A, at the mouth of Banana River Lagoon, is the only transect with a positive annual mean difference, albeit nearly negligible at only 0.02 m^3/s, indicating a slight increase in flow out of Banana River Lagoon with the removal of the causeways. The annual mean differences in flow volumes at the other transects are also nearly negligible (on the order of 0.1 m^3/s). Additional evaluations will focus on directional flow differences.

Both northerly and southerly annual mean flow, for each transect, increased with the removal of causeways 6, 7, and 8. The maximum difference in annual mean southward flow, an increase of 19.6 m^3/s (6.8%), occurred at Transect F, between Eau Gallie and Melbourne Causeways. The maximum difference in annual mean northward flow, an increase of 18.3 m^3/s (6.4%), occurred at Transect G on the south side of Melbourne Causeway. These results are consistent with previous results associated with velocity analyses.

Suspended Solids and Light Results for Several Scenarios

The most critical part of this study was determining the impact of the various causeway removal scenarios on seagrasses through modeled impacts to suspended solids and light penetration. The effects of causeway removals on Total Suspended Solids (TSS) concentrations and Percent of Incident Light at the Bottom (PILB) were evaluated by comparing monthly averages of simulated values for scenarios 3, 5 and 6 to the base case. These scenarios included removal of all causeways (scenario 3), removal of causeways 6, 7, and 8 (scenario 5), and partial removal of one causeway for the TSS results only (scenario 6).

The time period of March through August was chosen for these comparisons because these months coincide with the seagrass growing season. Also, these months capture different conditions, ranging from high winds, high runoff and high resuspension in March and April, 1998, to lighter winds, low runoff and less resuspension during May through August 1998. Light data was summarized for daylight hours only. Results were summarized to allow for both broad and localized spatial analyses. For scenario 3, results are summarized for 704 cells included in the study area. For scenario 5, results for 155 cells in the vicinity of the three causeways were summarized. For scenario 6, results were summarized for 43 cells in the vicinity of causeway 8. In addition, maximum localized changes in mean TSS were summarized for the individual cells for each scenario that showed the highest positive and negative changes from the base case (Table 2).

Removal of all causeways, scenario 3, showed a marked increase in mean TSS during the higher energy months of March and April, 39% and 38%, respectively. During the May through August time period, TSS increased by roughly 33%. The maximum fluctuations for any single cell showed that slight localized decreases were possible, but increases greatly overshadowed the decreases.

Analyses for scenario 5 were similar to those for scenario 3. TSS levels for March and April increased by 30% and 35% respectively in the area around causeways 6, 7 and 8, while levels for May through July increased by an average of 30%. TSS levels for August increased by only 7%. A color-coded plot of mean TSS differences for March (Figure 6) shows the wide spread areal extent of the TSS increases around the three causeways.

Simulation of a partial removal of causeway 8 had little impact on mean TSS levels, as they increased by less than 10% for all six months. Currently 10 of the 13 causeways in the study area have relief channels (#1, #3, and #13 do not have relief channels). In the area south of Wabasso, only the Seaway Bridge has no relief structures.

The monthly mean increase in TSS ranged between 30% to 39% for scenarios 3 and 5. This increase in TSS indicates a negative effect of causeway removal, since increased TSS leads to greater light attenuation.

Table 2. Total Suspended Solids results (monthly means, mg/l), base case and 3 scenarios.

Month	Base Case 704 Cells	Scenario 3 All Causeways 704 Cells	Scenario 3 Maximum Increase	Scenario 3 Maximum Decrease
March	16.7	23.2	33.5	-5.4
April	17.0	23.4	26.8	-4.8
May	4.0	5.2	10.6	-5.2
June	2.6	3.5	9.4	-5.3
July	2.2	3.1	10.0	-5.3
August	2.5	3.2	9.6	-4.9
	Base Case 155 Cells	Scenario 5 Causeways 6, 7, 8 155 Cells	Scenario 5 Maximum Increase	Scenario 5 Maximum Decrease
March	15.8	20.5	8.5	0.0
April	13.6	18.3	8.1	0.0
May	2.4	3.0	1.1	-0.1
June	1.7	2.2	1.7	-0.3
July	1.4	1.9	1.4	-0.4
August	1.5	1.6	0.8	-1.3
	Base Case 43 Cells	Scenario 6 Partial Causeway 8 43 Cells	Scenario 6 Maximum Increase	Scenario 6 Maximum Decrease
March	15.6	16.2	1.6	0.0
April	13.5	14.5	2.7	0.0
May	2.3	2.4	0.5	0.0
June	1.7	1.8	0.4	0.0
July	1.5	1.5	0.3	-0.1
August	1.7	1.6	0.1	-0.2

High levels of Percent Incident Light at the Bottom are desirable; therefore, lowered values of PILB associated with modeled scenarios are not desired. Monthly mean values for PILB decreased by 14% for both March and April for scenario 3 (Table 3). While monthly means also decreased for the other four months, their differences were less than ten percent.

For scenario 5, monthly mean PILB decreased in March and April by 15% and 18%, respectively, while changes in the monthly means were well below 10% for the other four months. A color-coded plot of mean PILB for April (Figure 7) shows the areal extent of the PILB increases associated with removal of the three causeways.

Very little change was evident for scenario 6, although there were more localized decreases than increases in light penetration.

Table 3: PILB results (monthly means, Percent of Incident Light at the Bottom), base case and 3 scenarios.

Month	Base Case 704 Cells	Scenario 3 All Causeways 704 Cells	Scenario 3 Maximum Increase	Scenario 3 Maximum Decrease
March	7.9	6.8	2.7	-6.9
April	9.7	8.3	3.5	-8.3
May	18.4	17.3	3.6	-6.8
June	17.3	16.6	3.6	-4.8
July	17.6	17.0	3.7	-5.4
August	15.4	14.9	3.4	-5.4
	Base Case 155 Cells	Scenario 5 Causeways 6, 7, 8 155 Cells	Scenario 5 Maximum Increase	Scenario 5 Maximum Decrease
March	3.9	3.3	0.0	-2.2
April	5.0	4.1	0.0	-2.8
May	10.1	9.6	0.0	-1.8
June	9.9	9.6	0.3	-1.5
July	9.7	9.4	0.3	-1.2
August	8.8	8.7	0.9	-0.4
	Base Case 43 Cells	Scenario 6 Partial Causeway 8 43 Cells	Scenario 6 Maximum Increase	Scenario 6 Maximum Decrease
March	4.9	4.8	0.0	-0.5
April	6.4	6.2	0.0	-0.7
May	13.3	13.2	0.1	-0.8
June	12.7	12.6	0.0	-0.5
July	12.0	12.0	0.0	-0.3
August	10.6	10.6	0.2	-0.2

K_d is a measured light attenuation coefficient that is used to calculate PILB. It cannot be directly compared with the PILB, unless you know the depth of water and the level of incident light just below the surface. However, if the depth of water and the level of incident light just below the surface are similar, then the error in the values of PILB may be approximated by the error in the values of K_d. The University of Florida compared model results to K_d values measured during five synoptic sampling trips in the IRL. The percent error in K_d was calculated to be 25%. All monthly means differences in PILB were below this error level. However, as the comparisons between the base case and scenarios 3 and 5 were comparative, monthly differences averaging around 15% for March and April may be considered relevant. Therefore, removal of causeways, represented by those scenarios, is not recommended.

A comparison of the relative importance of suspended material in the form of tripton, chlorophyll *a*, and color on light attenuation, and therefore their relative effects on seagrass growth, was conducted by the model developer (Sheng et al., 2003). Tripton represents the non-chlorophyll *a* portion of TSS and was estimated by Sheng to be responsible for about 75% of light attenuation (K_d) in the Banana River Lagoon and North and Central IRL (Titusville to Vero Beach).

Flushing Verification for Removal of Causeways 6, 7 and 8

As a final model evaluation, a flushing simulation was conducted to simulate the time required to flush 50% and 90% of a conservative tracer from selected zones for the base case and for the causeways 6, 7 and 8 removal scenario. For this flushing analysis, four zones in proximity to causeways 6, 7 and 8 were chosen for testing. Zone 1 was located between causeways 5 and 6, zone 2 is between causeways 6 and 7, zone 3 is between causeways 7 and 8 and zone 4 is between causeway 8 and a point just North of Goat Creek (Figure 8).

Flushing results are summarized in Table 4. As expected, Zone 1, the largest and farthest from the Sebastian Inlet, requires the most time to be flushed in the both cases. Zone 3, the smallest, is flushed fastest. When causeways 6, 7, and 8 are removed, the reduction in time to reach 50% flushing is only effected in Zone 1, which is improved by 15%. Flushing times to reach 90% flushing for zones #1, 2, and 3 are improved by 8-9%.

Table 4. Model Flushing Times Analysis.

FLUSHING ZONE NUMBER	FLUSHING ZONE VOLUME (m^3) x 10^6	FLUSHING TIME BASE CASE (days)		FLUSHING TIME CAUSEWAYS 6, 7, AND 8 REMOVED (days)		REDUCTION IN FLUSHING TIMES (BASE VS. 6, 7, 8 REMOVED) (percent)	
		50%	90%	50%	90%	50%	90%
1	78.3	20	129	17	119	15	8
2	59.5	6	81	6	74	0	9
3	40.3	3	50	3	46	0	8
4	77.8	10	72	10	72	0	0

In the executive summary of the CH3D-IMS model report, the University of Florida reported "The models simulated the water level with a 5-10% relative RMS error and salinity with a 10-30% relative RMS error." (Sheng, Y.P., et al, Final Report Vol. I). Since no other comprehensive error statement was made for hydrodynamic accuracy, it is reasonable to conclude that the hydrodynamics model has between 5-30% accuracy. Thus, while the modeled decrease in flushing time may be assumed to be within the error of the model, and thus not considered significant, the comparative differences between model runs suggest that a slight improvement in flushing does occur when causeways 6, 7, and 8 are removed. This result is similar to those obtained for the velocity and flow tests.

Conclusion

In conclusion, removing causeways results in slight increases in flushing and surface velocity, and a more evenly distributed flow regime across the lagoon. These effects cause a slight increase in salinity, while creating a moderate increase in suspended solids. The removal of causeways increases the fetch within the IRL, thereby increasing wave energy and sediment resuspension. All of these factors cumulatively result in slight decreases in light penetration during low energy months, but cause moderate decreases in light penetration during high energy months. Therefore, it is concluded that neither full nor partial removal of causeways will significantly benefit seagrass distribution in the Indian or Banana River Lagoons. In fact, negative impacts may be caused as a result of causeway removals.

References

Evink, G.L. 1980. *Studies of the Causeways in the Indian River, Florida*. A report to the Florida Department of Transportation (FL-ER-7-80). Tallahassee, FL, 141 pp.

Ghioto, R.D. 1973. *Digital Simulation of Tampa Bay*. Thesis, Univ. of S. Florida, Tampa, FL, 94 pp.

IRL National Estuary Program. 1996. *Indian River Lagoon Comprehensive Conservation & Management Plan*. A Plan document sponsored by U.S. EPA and the St. Johns River Water Management District. SJRWMD, Palm Bay, FL. 357 pp.

Indian River Lagoon Field Committee. 1987. *Indian River Lagoon System Management Plan: Goals, Objectives, and Policies*. A Final Draft to the Coastal Resources Interagency Management Committee and the Office of Coastal Management, Florida Dept. of Environmental Regulation. Tallahassee, FL. 19 pp.

Nielsen, S., B. Eggers, and S. Collins. 2000. The influence of seawalls and revetments on the presence of seagrass in the Indian River Lagoon, a preliminary study. *Florida Scientist* 63(1): 48-61

Powell, G.L., J. Matsumoto, W.L. Longley, and D.A. Brock. 1997. *Effects of Structures and Practices on the Circulation and Salinity Pattern of the Corpus Christi Bay National Estuary Program Study Area.* Corpus Christi Bay National Estuary Program. Corpus Christi, TX. 169 pp.

Sheng, Y.P. 1997. *A Preliminary Hydrodynamics and Water Quality Model of Indian River Lagoon*. Report submitted to SJRWMD (Contract #94W241). Palatka, FL.

Sheng, Y.P., and J. R. Davis. 2003. *Indian River Lagoon Pollutant Load Reduction (IRLPLR) Model Development Project, Final Report Volume I, A 3-D IRL Hydrodynamics/Salinity Model (UF-CH3D)*. Civil & Coastal Engineering Department, University of Florida, Gainesville, FL.

Sheng, Y.P., D. Christian, and T. Kim. 2003. *Indian River Lagoon Pollutant Load Reduction (IRLPLR) Model Development Project, Final Report Volume IV, An IRL Light Attenuation Model (UF-CH3D-LA)*. Civil & Coastal Engineering Department, University of Florida, Gainesville, FL.

Smith, N.P. 1987. An introduction to the tides of Florida's Indian River Lagoon. I. Water levels. *Florida Scientist* 50(1): 49-61.

Smith, N.P. 1993. Tidal and nontidal flushing of Florida's Indian River Lagoon. *Estuaries* 16(4): 739-746.

Steward, J.S., R. Brockmeyer, R. Virnstein, P. Gostel, P. Sime, and J. VanArman. 2003. *Indian River Lagoon Surface Water Improvement & Management Plan, 2002 Update*. St. Johns River Water Management District, Palatka FL, and South Florida Water Management District, West Palm Beach FL. 272 pp.

U.S. Army Corps of Engineers and St. Johns River Water Management District. 2002. *Central and Southern Florida Project: Project Management Plan of the Indian River Lagoon North Feasibility Study*. June 18, 2002. Jacksonville (USACE) and Palatka (SJRWMD). 63 pp. plus appendices.