MORPHOLOGIC EQUILIBRIUM STORM RECOVERY OF ST. LUCIE INLET, FLORIDA

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ABSTRACT

Episodic storm energy plays a vital role in inlet morphology variation. Inlet morphology change is traditionally controlled through jetties, weirs, breakwaters, and channel stabilization. St. Lucie Inlet's control structures were analyzed for post-storm hydraulic efficiency to determine the effectiveness of structures configuration. A 25-hour moving window and frequency response analysis following storm events showed the morphologic equilibrium time constant of the inlet for each storm. In a proper functioning jettied inlet, the time constant should remain relatively constant as the system configuration remains constant due to no morphology change. Final results of this study showed an increased morphologic equilibrium time constant over fifteen storm events from 1981-2007. A possible reason for the time constant increase was sediment transport into the inlet channel by storm energy. This transport changed the morphology of the system and thereby the time it needed to return to equilibrium. The sediment impedance decreased hydraulic efficiency between the estuary and the ocean, resulting in lower performance of the jetty system. The jetty system was designed to focus the ebb jet such that it scoured the channel and transported sediment offshore. The frequency response of the storms showed sediment was not being moved offshore; rather it remained in the channel. A possible solution is suggested by the author to increase the jetty's sediment transport performance. Maintenance and emergency dredging can be avoided by utilizing the energy of the flushing canals from Lake Okeechobee. The additional flow timed with an ebb tidal cycle could increase the ebb jet velocity to scour the channel and achieve sediment transport at the ebb shoal.

KEWORDS: Equilibrium time constant, moving window filter, inlet hydraulics, canal discharge, ebb jet

1 INTRODUCTION

Infrastructure, lives, economics, and the coastal ecosystem respond to and depend upon morphologic changes of inlets. Coastal engineering projects typically aim to maintain a specific inlet configuration with as little mechanical maintenance as possible (French 1960). Engineering projects are challenged by storm conditions which may cause failure of the structures to maintain the inlet configuration (Stone *et al*. 2004). St. Lucie Inlet (SLI) in Martin County, Florida is outfitted with asymmetrical twin jetties, a weir within the north jetty, and a detached breakwater to the south of the inlet mouth (SLI Mgmt Plan 1990). This type of configuration was originally designed to focus the ebb shoal jet in order to scour the navigation channel and deposit any sediment offshore in an ebb shoal (The Engineering School 1937). Sediment from the north will bypass the inlet mouth into southern ebb shoal lobes and a bypass bar, preventing back passing in to the inlet. This jetty configuration should result in a safe navigation channel sheltered from waves with little need of dredging (USACE CEM 2002).

This research was motivated to assess the performance of the jetty configuration's scouring of the channel and sediment deposition at the ebb shoal. It was hypothesized that the ebb shoal velocity was not high enough to scour the inlet as originally designed as routine and emergency dredging has been performed at the study site (Kraus 2008). The ability of the inlet to return to morphologic equilibrium after a storm event is evaluated using a 25 hour moving window analysis of the water elevation (Hughes 2002, Hinwood and McLean 2001). This analysis resulted in a morphologic equilibrium time constant (T_{morph}) for each storm event from 1981 to 2007. An increasing T_{morph} would suggest the system was not operating as design and the inlet channel was being impeded by sediment. The frequency response function for each storm will demonstrate whether in the inlet channel is efficiently exchanging water between the estuary and the ocean (Thuy 2014). If water exchange between the estuary and ocean is inefficient, potential solutions using the existing canal system may offer a low cost solution for St. Lucie Inlet managers.

1.1 Study Area

St. Lucie Inlet resides at the border of Martin and St. Lucie counties on the east coast of Florida. The inlet is bounded by Hutchinson Island to the north and Jupiter Island to the south with the Indian River Lagoon and St. Lucie River (SLR) to the west of the inlet (SLI Mgmt Plan 1990). Figure 1 shows the location of the St. Lucie Inlet system. Lake Okeechobee and its drainage canals (C-23, C-24, C-44) deliver freshwater into the St. Lucie River. SLR empties into the Indian River Lagoon which drains to the Atlantic Ocean via the St. Lucie Inlet.

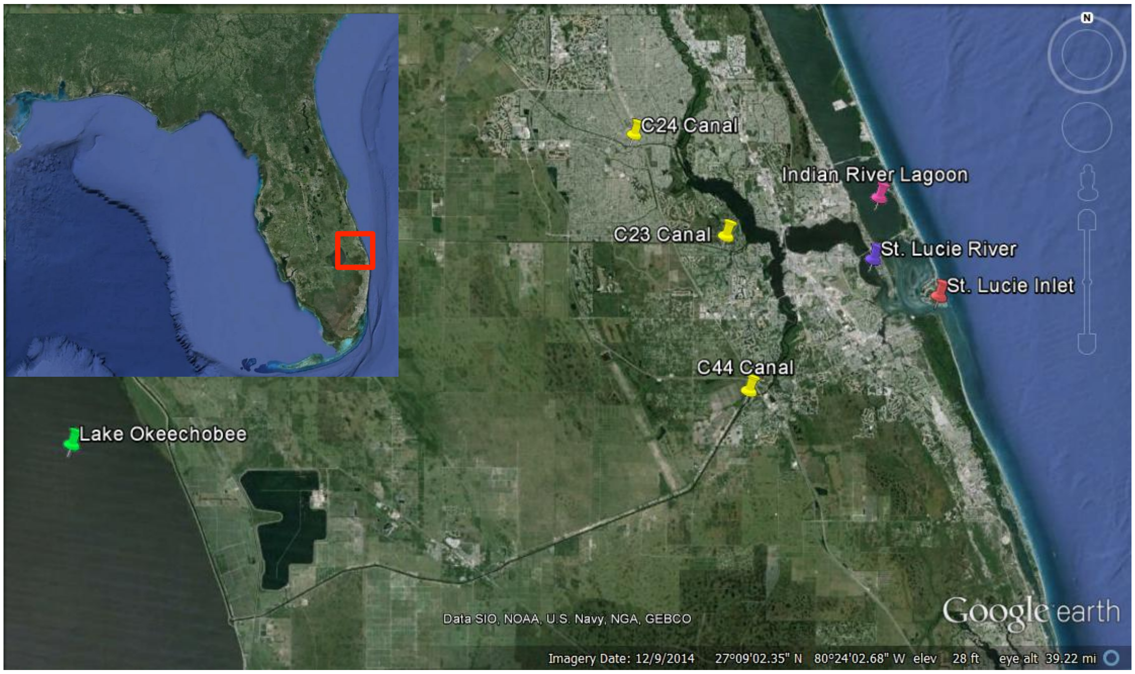

Figure 1. Inlaid Google Earth image of the state of Florida then zoomed in to Martin County. St. Lucie Inlet, St. Lucie River, Indian River Lagoon, Lake Okeechobee, and flushing canals C-23, C-24, C-44 are labeled with thumbtacks.

SLI experiences a tidal range of 0.3 to 0.5 meters with significant wave heights of one to two meters arriving from the northeast (CHL WIS Hindcast Data). The inlet and surrounding beaches are composed of quartz grains, shell hash, and fine-grain muck sediments with the dominant sediment transport from north to south except for back passing near the inlet mouth (SLI Mgmt Plan 1990). Sediment transport and inlet morphology were modified by construction of the north and south jetties, weir, and detached breakwater. Figure 2 shows the inlet morphology and structure configuration.

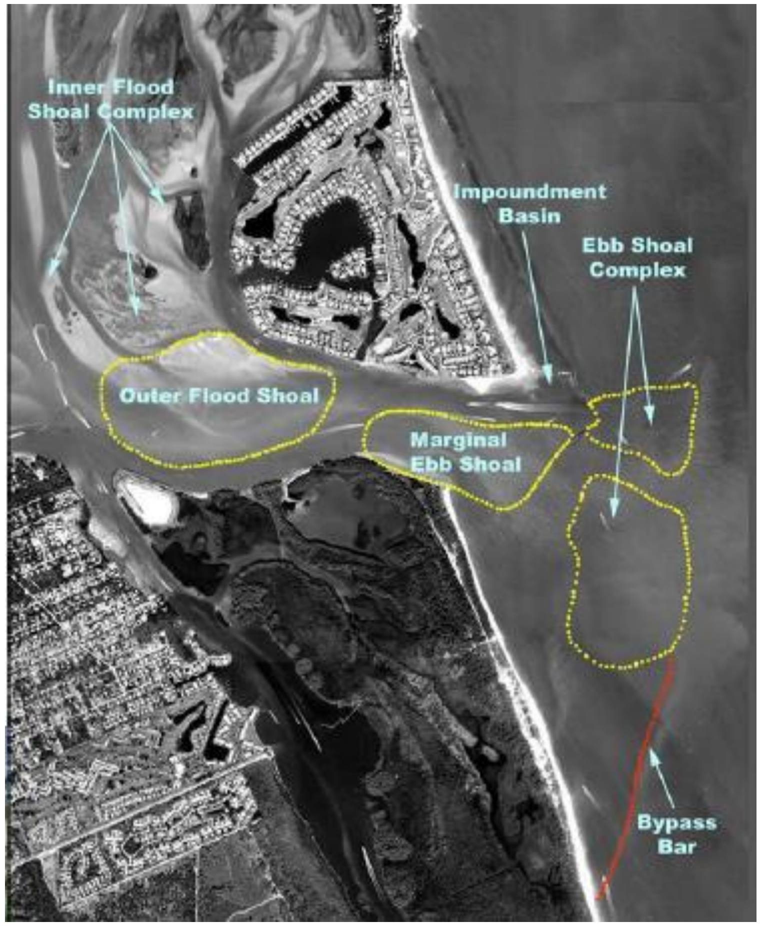

Figure 2. Satellite image of St. Lucie Inlet from the Inlet Management Plan of 1990. Morphologic features such as the flood shoals, ebb shoals, impoundment basin, and bypass bar are outlined and labeled.

The north jetty prevents sediment transport to the southern beaches, causing beach erosion and a westward retreat of Jupiter Island (Kraus 2008). While erosion south of the inlet is remedied with sand nourishments, the navigation channel is routinely dredged due to sediment buildup from the outer flood shoal, marginal ebb shoal, and impoundment basin. The inlet morphology change cause by the structure configuration and sediment transport into the navigation channel are the focus of this research.

2 METHODS

Methods employed by Thuy *et al.* (2013, 2014) were used to determine the T_{morph} and inlet hydraulics of SLI following storm events. T_{morph} was developed from a one dimensional model equation of an inlet's water elevation change in relation to the morphologic configuration and external forces. The equation theorized an inlet changes at a rate described by the distance from the inlet's equilibrium state, represented as a log function. Equation 2 is the one dimensional model equation representing the water elevation change with time, its relation to the equilibrium water elevation and the morphologic equilibrium time constant.

$$\frac{d\eta}{dt} = \frac{\eta_{eq}-\eta}{T_{morph}} \tag{1}$$

η is water elevation in meters obtained from tide gauges, η_{eq} is the equilibrium water elevation in meters, and T_{morph} is the morphologic equilibrium time constant in hours. T_{morph} is the time required for the water elevation to return to equilibrium between the external wave and tidal forcings. The data need for Equation 1 was taken from inlet tide gauges, river elevation gauges, canal elevation gauges, and a WIS hindcast wave node offshore of SLI. These data sets were trimmed to five days before and after storm events to capture potential morphologic change as the water elevation returned to equilibrium. Each storm event was analyzed for T_{morph} by solving Equation 1 for the time constant. Once T_{morph} was determined for each storm event, a hydraulic analysis was done to create time series of the phase lag, hydraulic gain, and frequency response function. Details for the T_{morph} and hydraulic calculations are provided in the following subsections.

2.1 T_{morph} Analysis

A 25-hour moving window analysis was applied to each storm event using a fifteen or thirty minute time step, depending upon the data set sampling frequency. The window size incorporates the periods of the diurnal and semidiurnal tidal signals present at SLI. Raw water elevation time series from within the inlet were demeaned with the moving window average water elevation. Then the 25-hour window was applied to create a mean, minimum, and standard deviation time series of the water elevation within the estuary. The three time series were displayed on one plot for curve fitting of the mean and standard deviation time series. The curve fitting start point was selected by comparing when the standard deviation stopped oscillating while simultaneously the mean elevation began rising exponentially. This behavior of the time series physically represented the point when storm water had entered the estuary, potentially causing morphologic change, and forcing the system out of equilibrium. Fitting these curves produced the equilibrium time constant, or the amount of hours needed for the storm water to be flushed out of the estuary, and through the inlet so the water level could be at equilibrium again. Gentle exponential slopes resulted in larger T_{morph} values while steeper slopes indicated quicker returns to equilibrium and smaller T_{morph}. By obtaining a T_{morph} for many storms over several decades, the system could be evaluated for its design performance over study period. The time constant should not change significantly over the study period if the channel morphology functions as designed (Lanzoni and Seminara 2002, Morton and Sallenger 2003).

2.2 Hydraulic Analysis

The following calculations utilized the demeaned water elevation time series from each storm to determine the hydraulic response of the estuary and potential morphologic change within the inlet channel. After demeaning, diurnal and semidiurnal amplitudes were calculated from the water elevation time series using harmonic analysis to determine the magnitude of the estuary and ocean elevations. Once elevation amplitudes were obtained, the hydraulic gain between the estuary and ocean was calculated. The gain showed the efficiency of water exchange between the estuary and ocean during and after storm events. Equation 2 shows how water amplitudes were used to calculate hydraulic gain (Thuy 2013).

$$G = \frac{\sqrt{a_b^2+b_b^2}}{\sqrt{a_o^2+b_o^2}} \tag{2}$$

G is hydraulic efficiency, a_b is diurnal amplitude in the estuary, b_b is semidiurnal amplitude in the estuary, a_o is diurnal amplitude in the ocean, and b_o is semidiurnal amplitude in the ocean. Equation 2 showed that equal tidal amplitudes in the estuary and the ocean equates to one; meaning perfect efficiency of water transport through the inlet. A gain of zero indicated no transfer of water between the estuary and ocean, representing impedance within the inlet channel. Impedance indicated a shoal due to sediment transport or some form of morphological change of the inlet channel. Another indication of water exchange efficiency was the phase lag between the diurnal and semidiurnal amplitudes as show in Equation 3 (Thuy 2013).

$$\phi_b = \text{atan}\,(\frac{b_b}{a_b}) \tag{3}$$

Where ϕ_b is the phase lag, b_b is the semidiurnal estuary amplitude, and a_e is the diurnal estuary amplitude. Gain and phase lag were then used to calculate frequency response for the diurnal and semidiurnal signals. Frequency response is represented in Equation 4 in the complex plane (Thuy *et al.* 2013).

$$F = G^{-i\phi} \tag{4}$$

Where F is the frequency response, G is the hydraulic gain from Equation 2, i is the imaginary number, and ϕ is the phase lag from Equation 3. Equation 4 demonstrated that the magnitude of the frequency response is represented by the gain while the phase lag determines the angle of the frequency response. The frequency response curve will loop and migrate towards the origin or unity depending on the hydraulic state of the inlet. Loops move in a counter clockwise direction towards the origin, demonstrating lower efficiency and shoal creation within the inlet as the frequency response moves towards the origin and lower hydraulic efficiency. Clockwise motion towards unity represents increased hydraulic efficiency and scouring of the channel (Thuy *et al.*2013). Once the storm has passed and the inlet has returned to equilibrium, the location of the ending point of the frequency response curve may be near or far from the starting point. Small distances between the points show little morphologic change within the inlet after the storm event while large distances indicate morphological change within the channel (Dohner 2015). Combining the T_{morph} calculations with the frequency response curves for storm events over many years will reveal the functionality of the twin jetty and stabilized channel design of SLI.

3 RESULTS

Storm events from 1981-2007, having eye walls within one hundred nautical miles of SLI, were analyzed using the methods stated in the previous section. Table 1 lists storm dates as well as inlet construction projects for the study period. Analysis of storms between construction events showed changes of morphology and hydraulics due to stabilization of the channel, dredging, and beach nourishments. The construction events are the focus of the storm analysis, as the stabilization of the inlet should be increasing the efficiency of water hydraulics between the estuary and ocean. If the construction was not performing as designed, the T_{morph} will increase and morphologic changes will occur within the channel (Thuy 2013, Kraus 2008).

Table 1. List of storm and construction events from 1974 to 2008 involving St. Lucie Inlet and the surrounding area. Start and end dates with event description and event type are listed chronologically. Not all storm events listed were analyzed for morphologic change.

Data Start	Data End	Event Year	Event Description	Event Type
---	---	1974	Extension of north jetty, sand impoundment basin created, south training jetty installed	Construction
6/11/1976	6/12/1976	1976	Unnamed	Storm
8/18/1976	8/21/1976	1976	Dottie	Storm
---	---	1977	Flood shoal nourishment	Construction
6/11/1979	6/16/1979	1979	Unnamed	Storm
8/25/1979	9/07/1979	1979	David	Storm
---	---	1980	Beach nourishment	Construction
7/02/1981	7/03/1981	1981	Unnamed	Storm
8/07/1981	8/21/1981	1981	Dennis	Storm
---	---	1982	Extension of north jetty, installation of south jetty, detached breakwater added, impoundment basin and channel dredged	Construction
8/23/1983	8/29/1983	1983	Barry	Storm
9/25/1984	10/01/1984	1984	Isidore	Storm
10/25/1984	10/27/1984	1984	Unnamed	Storm
---	---	1985	Beach nourishment	Construction
7/21/1985	7/25/1985	1985	Bob	Storm
---	---	1988	Chris	Storm
---	---	1989	Beach nourishment	Construction
---	---	1994	Groin constructed	Construction
---	---	1994	Gordon	Storm
---	---	1995	Erin	Storm
8/22/1995	8/27/1995	1995	Jerry	Storm
---	---	1998	Flood shoal dredged	Construction
10/22/1998	11/09/1998	1998	Mitch	Storm
10/12/1999	10/19/1999	1999	Irene	Storm
12/01/1999	12/06/1999	1999	Emergency dredge and nourishment	Construction
8/08/2000	8/11/2000	2000	Unnamed	Storm
---	---	2000	Emergency dredge of impoundment basin	Construction
8/25/2004	9/10/2004	2004	Frances	Storm
9/02/2004	9/24/2004	2004	Ivan	Storm
9/13/2004	9/29/2004	2004	Jeanne	Storm
---	---	2005	Katrina	Storm
---	---	2005	Ophelia	Storm
---	---	2005	Tammy	Storm
10/15/2005	10/26/2005	2005	Wilma	Storm
8/24/2006	9/04/2006	2006	Ernesto	Storm
5/06/2007	5/13/2007	2007	Andrea	Storm
		2007	Impoundment basin dredged	Construction
8/15/2008	10/28/2008	2008	Fay	Storm

Table 2 displays the results of the moving window analysis and associated T_{morph} for each storm. The baseline value for SLI should be approximately 60 hours as the surface area of the estuary is less than two square kilometers (Thuy 2013). A general increasing trend for T_{morph} from 1981-2007 is show.

Table 2. A list of the storms analyzed with the category and eye distance from St. Lucie Inlet are shown (NWS NHC data). The T_{morph} shown is from the curve fit to the mean water elevation time series created by using the 25 hour moving window technique. Hydraulic Efficiency was determined from the semidiurnal

frequency response time series.

Year, Storm Name	Category	Distance (na mi.)	T_{morph} (hr)	Hydraulic Efficiency
1981 Unnamed	TD	10	20.5	Decreased
1981 Dennis	TS	40	67.5	Decreased
1983 Barry	TD	40	60.8	Decreased
1984 Isidore	TD	20	65.7	Decreased
1984 Unnamed	TD	30	195	Decreased
1985 Bob	TS	10	62.3	Decreased
1998 Mitch	TS	40	86.2	Increased
1999 Irene	H1	20	78.7	Decreased
2000 Unnamed	TD	100	128.2	Increased
2004 Frances	H2	20	181.2	Decreased
2004 Ivan	TD	100	113.8	Decreased
2004 Jeanne	H3	20	61.4	Decreased
2005 Wilma	H2	40	68.9	Decreased
2006 Ernesto	TS	30	101.5	Decreased
2007 Andrea	TD	100	158.3	Decreased

Closer analysis of Table 2 shows inconsistencies with the time constant. The time constant value decreased following dredging within the channel, thereby increasing the efficiency of water exchange within the inlet. Then, as time went on, the hydraulic efficiency decreased while the T_{morph} increased. The increase of the time constant can be attributed to morphologic change in the inlet channel such a sediment transport into the marginal ebb shoal and the offshore ebb shoal occurring too close to the channel mouth for sediment to be removed entirely from the circulation cell. These two shoals counteract the functionality of the twin jettied system, which aims to extend the ebb jet through the channel to scour any shoals and deposit sediment offshore to prevent backflow during normal and storm conditions. Hydraulic results from the frequency response function can determine if morphologic change occurred, resulting in an increased T_{morph}.

3.1 Frequency Response

Of the fifteen storms analyzed, thirteen demonstrated decreased efficiencies in the frequency response plots, implying morphologic change in the inlet channel during the storm events (Hayes and FitzGerald 2013). These results suggested waves were transporting sediment into the inlet channel where it was added to the marginal ebb shoal or impoundment basin (Johnson 1973). This deposition resulted in impeded flow through the inlet channel. Water was forced to build up within the estuary, causing longer high water conditions and slower exchange of water with the ocean. These results were counterintuitive to the expected results of a fully functional twin jettied system. The jetties were meant to prevent sediment transport into the channel and allow quicker exchange of water between the estuary and ocean.

Hurricane Frances in 2004 was one of the decreased efficiency storm events for SLI. The frequency response curve for this storm is shown in Figure 3a.

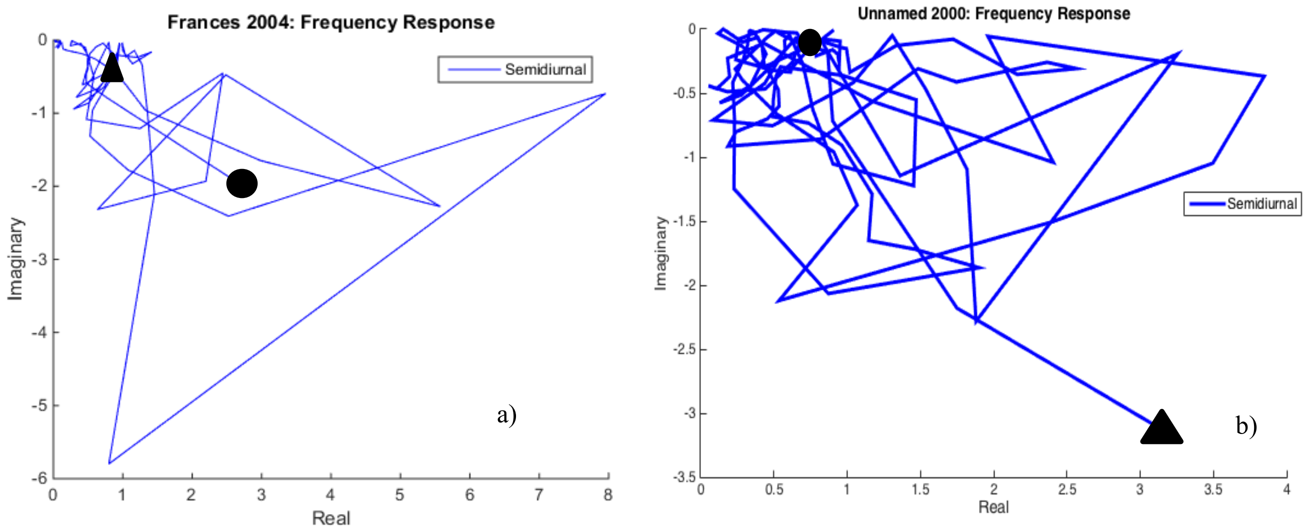

Figure 3: (a)Semidiurnal frequency response plot from Hurricane Frances in 2004 and (b) Unnamed tropical depression in 2000. The black circle indicates the starting point while the black triangle indicates the ending point. The plot is in the imaginary plane with the horizontal axis being the real axis and the vertical axis being imaginary. The magnitude of the frequency response is the hydraulic gain while the angle from the origin is the phase lag as described in Equations 2,3, and 4.

Hurricane Frances caused morphological change judging by the large distance between the starting and ending points of the curve in Figure 3a. The ending point clearly shows the impedance within the channel as the efficiency is close to the origin, thus little water is being exchanged between the two bodies of water. The remaining twelve storms of decreased efficiency displayed similar traits with counter clockwise rotation of the semidiurnal frequency response function. For decreased efficiency, the semidiurnal frequency response curves rotated clockwise, starting near the origin and ending closer to or greater than one. The two storms which displayed increased hydraulic efficiency demonstrate opposing characteristics to the decreased efficiency plots. An Unnamed tropical depression in 2000 was a prime example of an increased efficiency event. For increased efficiency, the semidiurnal frequency response curves rotated counter clockwise, starting near one and ending closer to zero. These two events shared the large distance in starting and ending points like the decreased efficiency events, suggesting both efficiency event types experienced morphologic change via sediment transport within the inlet channel, merely in opposite directions.

4 DISCUSSION

The asymmetrical twin jetties and breakwater system of St. Lucie Inlet was designed to scour the channel during ebb flow and prevent sediment back passing into the channel (Escoffier 1977). Inlet channel stabilization was evaluated using a short-term morphologic equilibrium time constant and hydraulic frequency response. The T_{morph} of the inlet increased from approximately 60 hours to over 100 hours. Morphologic change, counter to the design of the stabilized inlet channel, occurred when sediment was transported to the marginal ebb shoal and sand impoundment basin. The increasing time constants in Table 2 and the frequency response curves of thirteen storm events showed decreased hydraulic efficiency within the inlet due to morphologic change in the channel. The asymmetrical jetties and detached breakwater were designed to focus the ebb-tidal jet such that velocities scour the navigation channel and deposit sediment offshore in the ebb shoal (Escoffier 1977). Therefore, the results showed the system's design was not operating as planned, and morphologic change occurred within the channel during storm events. Numerous dredges of the channel and impoundment basin showed an ineffective scouring of the channel and mechanical removal was required for safe navigation of the inlet. Lack of scouring resulted in channel shoaling, decreased water velocities, and lower sediment transport with each storm event (Escoffier 1977). With lower sediment transport during and after storms, water was allowed to build and reside in the estuary longer, as the increased T_{morph} showed.

The next step for management would be to increase the sediment transport through the channel and offshore to counteract the current shoaling and longer equilibration time post storm events. Possible solutions include continued dredging of the inlet channel and impoundment basin, increasing the length of the south jetty to control the ebb-jet direction and ebb shoal location as well as to prevent sediment back passing. Perhaps a more cost-effective solution lies in suggestions by Fitzgerald, Kraus, and Hands (2000) for decreased dredging by utilizing the existing conditions of the system and foregoing extension of the south jetty completely. For St. Lucie Inlet, a possible option for increasing sediment transport out of the channel exists within the Lake Okeechobee flushing canals (C-23, C-24, C-44). These three canals empty directly into the SLR from Lake Okeechobee as shown in Figure 2. The freshwater discharge is manually regulated by control structures in the canals to maintain a safe water level in the lake. Managing the canal releases into St. Lucie River for maximum velocities and higher hydraulic head into the inlet channel could provide the necessary energy for sediment transport out of the inlet channel and into the offshore ebb shoal, which may be pushed further offshore. This could raise the performance of the inlet system to that of the original design. Incorporating canal flushing may provide a cost effective solution to the expensive emergency dredge method for channel morphologic change due to storm events.

5 CONCLUSIONS

The functionality of the asymmetrical jetty and detached breakwater was evaluated using the storm response of the inlet hydraulics and morphologic equilibrium time constant. Results from fifteen storm events from 1981-2007 showed St. Lucie Inlet increased the time it needed to return to its water elevation equilibrium post storm events. The storm events showed a decreased efficiency within the inlet channel due to morphologic change caused by sediment transport during the high-energy wave regimes of the storms. Results suggested the inlet structural configuration was ineffective in scouring the channel, depositing sediment in the offshore ebb shoal, and preventing sediment back passing into the channel. A potential solution to scour the inlet and increasing the efficiency of water exchange after storms exists in the flushing canals from Lake Okeechobee. The increased water flow from the canals will aid St. Lucie River to push water from the estuary and sediment from the channel after a storm has passed. The methods presented for this research would display if the canal flushing was successful in scouring the channel and increasing the hydraulic efficiency. The T_{morph} would be lowered to represent a faster return to equilibrium of the water elevation in the estuary. The frequency response curve for storm events would show increased efficiency after the storm and little morphologic change in the channel after the storm. Utilizing the canal system would remove the need for expensive emergency dredging after storms and lower the frequency of maintenance dredging of the channel and impoundment basin. This research recommends using the existing canal systems to solve St. Lucie Inlet's design shortcomings for quick, inexpensive results and minimal future dredging requirements.

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