August 16, 2019

CLAM PASS

2019 Review of Inlet Management

Prepared for

Pelican Bay Services Division

Collier County, Florida

Abstract

This report provides review and analysis of available data and information related to Clam Pass and its maintenance dredging program under the 2014 Clam Bay Natural Resource Protection Area Management Plan. The analysis includes the evolution of inlet morphology and effects of storm events and maintenance dredging on inlet stability. The study provides a timeline of natural and engineering events and summarizes general findings and recommendations.

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Executive Summary

Clam Pass is a small inlet in Collier County, Florida, that provides the only tidal connection to over 500 acres of mangrove wetland preserve of Clam Bay designated as Natural Resource Protection Area (NRPA). This study is provided to evaluate the inlet management implementation at 5 years since the updated management plan was developed in 2014. The study also evaluates the more recent increase of maintenance dredging frequency. The analysis includes a comprehensive review of historic inlet dynamics and maintenance dredging records at the inlet, including but not limited to:

- Background of Clam Pass physical features, including data from 7 dredging events and annual monitoring surveys.
- Analysis of wave climate variability and tropical storm frequency.
- Analysis of the maintenance dredging template and history.
- Assessment of adjacent shoreline conditions and variability.
- Assessment of morphological trends in the inlet system.

The above information was compiled and reviewed. Key subjects related to inlet stability and management are discussed and summarized including:

- Clam Pass critical stability under typical conditions and vulnerability to storm impacts.
- Effects of increased storm activity 2016/2017 including atypical sediment transport reversal.
- Section B of the flood shoal progressive widening to south and inlet channel meander.
- Corrective measures implemented in 2018 to reduce inlet channel meander along the inlet banks to improve stability.
- Post dredging inlet template equilibrium adjustment post dredging.
- Maintenance dredging planning following established threshold criteria identified in the NRPA management Plan
- Annualized cost of inlet maintenance dredging over past two decades

Based on the on-going monitoring program and findings of this study the following recommendations are provided:

- Continue to monitor inlet stability relative to inlet shoaling or hydraulic efficiency thresholds.
- Maintain ability to implement rapid response to severe storm impacts to avoid potential for inlet closure
- Continue with adaptative plans allowing for grading inlet banks to streamline flow and minimize channel meander.
- Continue to adjust grading area along both inlet banks to reduce potential for marginal channelization of flow.
- Monitor the resiliency of minimizing channel meanders through section B and consider extension of grading area into accessible stations or alternatives to stabilize mangrove shoreline if regression continues.
- Continued coordination with sand nourishment events. The timing and volume of beach nourishment in the disposal template of Clam Pass maintenance can be critical to inlet stability.

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1. Background

Clam Pass is a small inlet located in Collier County, Florid, that provides the only tidal connection to over 500 acres of mangrove wetland preserve of Clam Bay designated as Natural Resource Protection Area (NRPA). The Clam Bay system includes several interconnected bays surrounded by extensive areas of mangrove wetlands. The preserve is a pristine environmental resource that is collectively known as Clam Bay. **Figure 1** shows an aerial photo of the Clam Bay system. Clam Pass has gone through periods of inlet migration as well as closure in the 1990's which caused degradation of the ecological system and large areas of mangrove die offs leading up to the management plan development and implementation since 1999.

Figure 1. Clam Bay system

Maintenance dredging of Clam Pass is essential to the health of the ecological system because of the relatively small tidal prism for Clam Bay. For such a small tidal inlet, there is typically a critical balance between tidal energy and littoral process at the inlet channel. This creates a system that is critically sensitive to storm events frequencies and sequence during active weather seasons. Under the typically calm wave climate of southwest Florida, astronomical tidal cycles are generally sufficient to maintain the inlet open. **Figure 2** shows the Clam Pass morphologic features and illustrates the critical balance between wave forces and tidal flow that maintains the inlet open under typical conditions. However, during storm events the inlet can become overwhelmed by wave driven sediment transport, resulting in progressive shoaling of the inlet and flood shoal areas.

The frequency, duration and sequence of storms influence the inlet shoaling and its ability to recover to near equilibrium conditions. Maintenance dredging becomes necessary when shoaling becomes too restrictive for tidal flow to maintain stability of the inlet. Closure or significant shoaling of the inlet can cause significant deterioration of the Clam Bay ecological system. After repeated inlet closure and a mangrove die-off that occurred during the late 1990's, a management plan and dredging

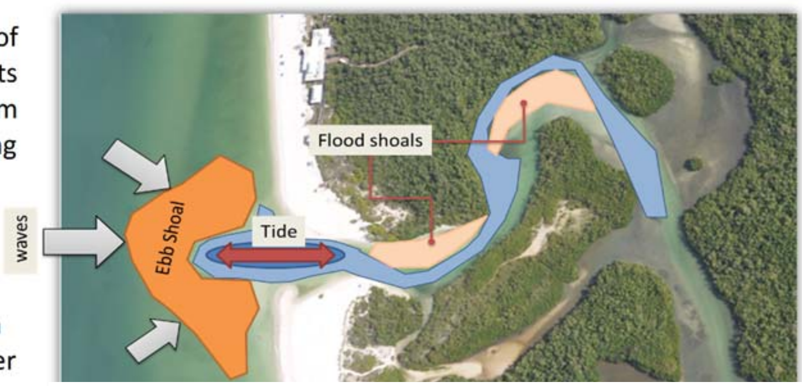

Figure 2 . Clam Pass physical features and illustration of the critical balance of wave and tidal forces

program were initiated to maintain tidal exchange with the bays. In 1999 Collier County, in cooperation with the community of Pelican Bay which borders Clam Bay, implemented The Clam Bay Restoration and Management Plan. The purpose of the plan was to keep Clam Pass open by improving tidal flushing throughout the wetland preserve. The plan included dredging the inlet channel and parts of the extensive shoals which had accumulated within the flood shoals over many years. Those interior shoals when present, reduce the tidal prism by obstructing tidal flow to bay areas beyond the immediate vicinity of the inlet. The combined effect of The Clam Bay Restoration and Management Plan resulted in significant increase of the tidal prism relative to conditions prior to the 1999 dredging. The plan also included monitoring and maintenance dredging which occurred in 2002 and 2007 under the 1998 management plan and 10-year permits. As a result, the inlet remained open while maintained, and the areas of stressed or dying mangroves have recovered. Following the expiration of the initial dredging permits, efforts to obtain updated permits were pending when active storms in 2012 resulted in closure of the inlet in the fall of 2012. **Figure 3** shows a timeline of the dredging events under the 1998 NRPA management plan until inlet closure in 2012.

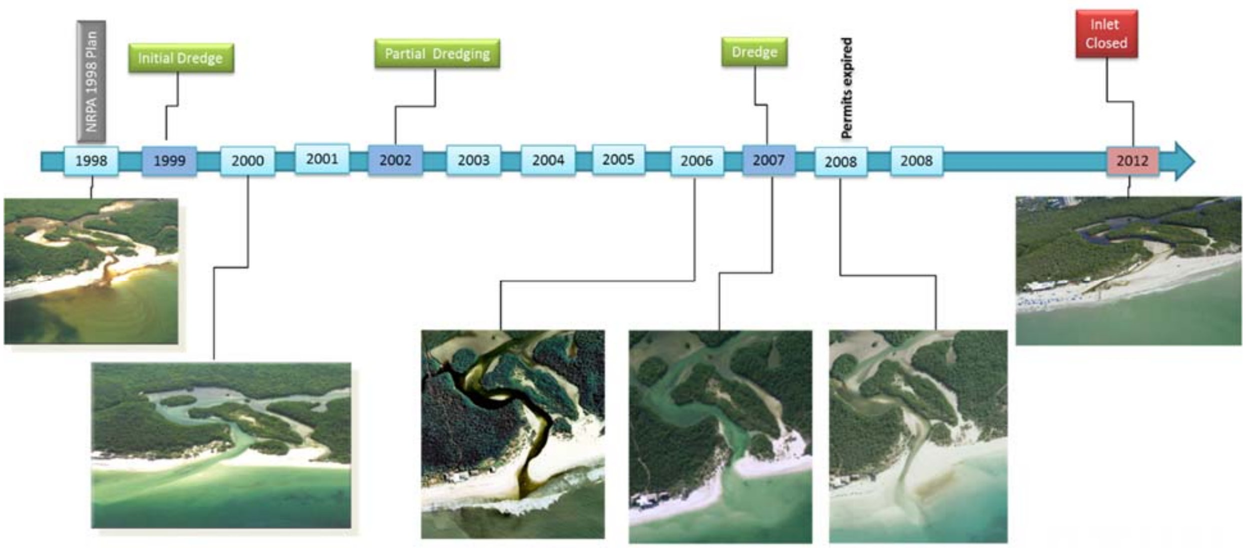

Figure 3- Timeline of Clam Pass Dredging Events 1998-2012

Following inlet closure in the fall of 2012, Collier County obtained an emergency permit to mechanically reopen the inlet, following the same channel template that had been dredged since 1999. This allowed obtaining required dredging permits to reopen the inlet in a relatively short time. The inlet reopening was completed in April 2013 and tidal exchange between the bay and the Gulf of Mexico was restored to functional levels. The complete closure of the inlet in late 2012 resulted in the collapse of its ebb shoal with large volume of sand being pushed by waves onshore.

An updated NRPA management plan was developed in 2014 and adopted by Collier County in 2015. The 2015 updated plan included the development of design criteria for inlet stability (conditions for which maintenance dredging is required to maintain hydraulic efficiency and avoid potential inlet closure). The 2015 plan implementation also includes various monitoring to maintain the health of the ecosystem. In addition to the ecological and biological monitoring of the bay system and its function as a protected environmental resource, the monitoring program includes hydraulic and physical monitoring of the inlet and bay system to assess the stability of the pass and maintenance dredging requirements. Monitoring of the hydraulic and physical conditions of the Clam Bay system includes continuous water level and tidal data collection at 4 locations within the bay system. The maintenance dredging Permits under the updated plan were obtained in early 2016 and the inlet was dredged in April of 2016. Active tropical seasons and winter cold fronts in 2016/2017 caused rapid inlet shoaling. Partial dredging that included inlet channel excavation in 2017 was completed as a rapid response to restore the inlet function and avoid inlet closure. Dredging of the full template was completed in 2018 following impacts from Hurricane Irma and winter storms in the early months of 2018. **Figure 4** shows the time line of recent dredging events for the period between 2012 and 2019.

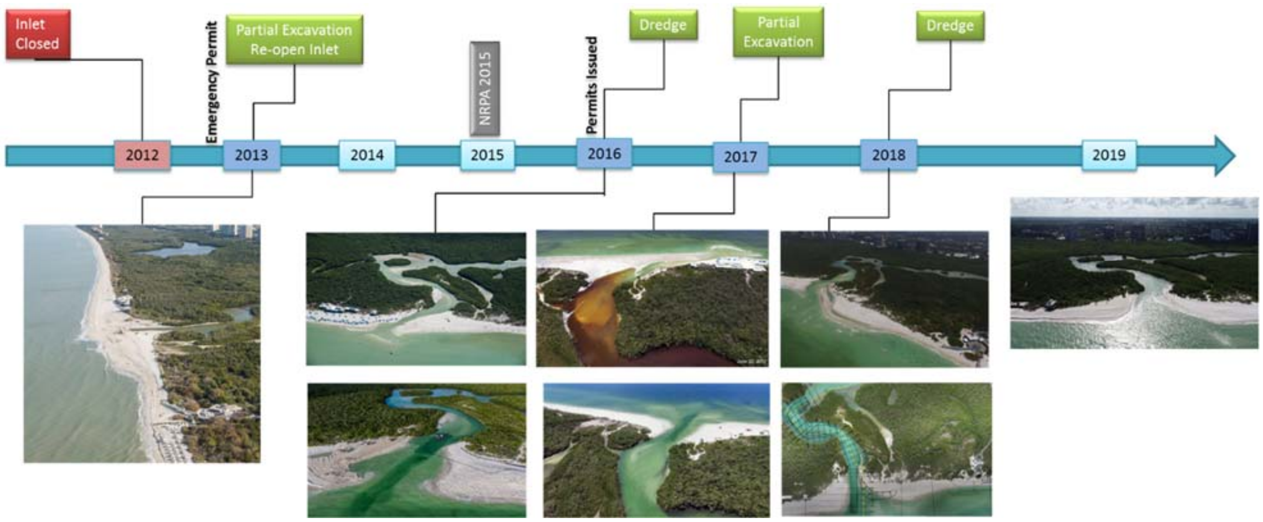

Figure 4- Timeline of Clam Pass Dredging Events 2012-2019

Overall, Clam Pass was dredged 7 times over the past 21 years since the initial management plan was developed in 1998. The last dredging event was completed in May 2018. **Table 1** lists information of all dredging events of Clam Pass since the initial management plan was developed in 1998.

Table 1. Summary of Clam Pass Dredging information

Completion Date	Volume from dredging template	Volume from inlet banks regrading	Total cut volume	Disposal Area DEP Reference monuments for events in the past 10 years
April 1999*	32,000	-	**32,000**	NA
Feb 2002	11,700	-	**11,700**	NA
April 2007	20,600	-	**20,600**	NA
March 2013**	20,300	-	**20,300**	R40-R41.4 & R42-R44
May 2016	14,300	4,700	**19,000**	R41-R-41.4 & R42-R43.5
August 2017***	5,400	5,600	**11,000**	R40.5-R41.4 & R42-R43
May 2018	8,500	3,200	**11,700**	R42-R43

Notes:

* Initial dredging template extended south to Outer Clam Bay plus few limited cuts within the bay channels to Inner Clam Bay and Upper Clam Bay.

** Mechanical dredging to reopen the inlet following the pass closure in 2012 and onshore collapse of the ebb shoal.

*** Limited mechanical excavation of the inlet channel and regrading inlet banks following tropical storm Cindy.

This study is provided to evaluate the inlet management implementation 5 years after the updated management plan which was developed in 2014. The study also aims at evaluating the increase of maintenance dredging frequency over the past few years.

2. Technical Review of Clam Pass Maintenance Program

This technical analysis is prepared to provide a general review of the natural conditions and maintenance dredging events affecting Clam Pass. The analysis includes a comprehensive review of historic inlet dynamics and maintenance dredging records at the inlet, including but not limited to:

- Historical background of Clam Pass physical features and inlet morphology, including aerial photos, data from 7 dredging events and annual monitoring surveys.
- Analysis of wave climate variability and tropical storm frequency.
- Analysis of the maintenance dredging template and history.
- Assessment of adjacent shoreline conditions and variability.
- Assessment of morphological trends in the system.

The above information was compiled and reviewed. Key findings and recommendations are discussed in the following sections. Supporting information in the form of charts and tables are also provided in the Appendices sections. **Figure 5** shows a plan view of the authorized dredging template established in the 2014 updated NRPA management plan. The dredging area included the inlet channel (section A) and flood shoal dredging areas (sections B and C). The 2014 updated plan and subsequent permits also included grading areas along the inlet channel banks to allow post dredging conditions to mimic natural inlet conditions following construction.

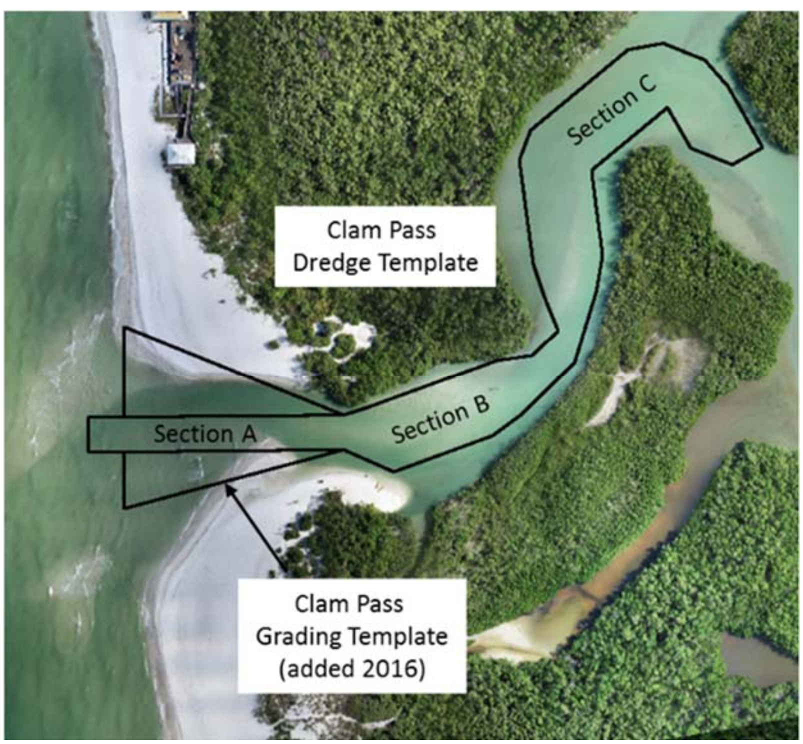

Figure 5 . Clam Pass maintenance dredging template (aerial photo July 2019)

2.1 Analysis of physical monitoring data

Figure 6 shows recent aerial photo taken in July 2019 of Clam Pass. The aerial photos and survey data of May 2019 indicate the stable inlet conditions 1 year post 2018 maintenance dredging. **Appendix A** includes summary of the 2019 inlet condition survey showing cross section plots of existing conditions at various locations within the inlet sections. Review and analysis of all available data over the past 20 years were completed as part of this study. **Appendix B** includes plots of changes in inlet geometry and inlet cross sections based on available data over the past 20 years. The inlet morphology data analysis indicated

Figure 6 . Clam Pass aerial in July 2019, one year post 2018 maintenance dredging

the following:

- Dredging the authorized template increases flow areas and sand holding capacity in the flood shoal areas.
- Rapid shoaling typically occurs in the first year post dredging and evolves towards equilibrium conditions of flow area and sand accumulation within the template.
- Cumulative shoaling rates vary over years between dredging events depending on wave events, frequency, intensity and duration of storms.
- Increased shoaling in Section B of the flood shoal area since 2010 forced the flow to channelize along the south bank of the flood shoal area. This resulted in significant erosion of the mangrove shoreline and expansion of the width of Section B.
- The change in the geometry of Section B since 2010 increased the inlet channel meander towards the north and reduced inlet stability potential.
- Blocking the channel meander as part of the south bank grading during the 2018 maintenance dredging helped reduce the channel meander and increase stability of the inlet.

2.2 Analysis of wave climate variability.

Wave and sediment transport modeling were completed as part of this study to evaluate the nearshore wave climate and sediment transport variability over the past 13 years in the vicinity of Clam Pass.

Offshore wave data from NOAA's Wave Watch III database for a 13-year record from January 2006 to December 2018 were used to evaluate annual wave variability and identify decadal representative average sediment transport. The wave climate offshore of southwest Florida typically includes several winter storms with waves originating from the northwest and summer waves that are typically from the southwest. In a typical year, the total wave energy from the northwest exceeds the wave energy from the southwest which results in net annual southward transport depending on shoreline orientation.

Tropical storms and hurricane events can cause a significant amount of sediment transport and influence the typical balance of the wave climate depending on the path and duration of each tropical event.

Figure 7 shows a wave record and wave rose of 2006 as an example of the typical annual wave climate at Clam Pass. **Appendix B** includes wave records of years included in this analysis from 2006 to 2018. The figure indicates that on an average year, calm waves conditions occur over 60% of the time and wave events during winter months provide the majority of the annual wave energy. Winter waves typically originate from the northwest to west directions. This results in net longshore sediment transport from north to south.

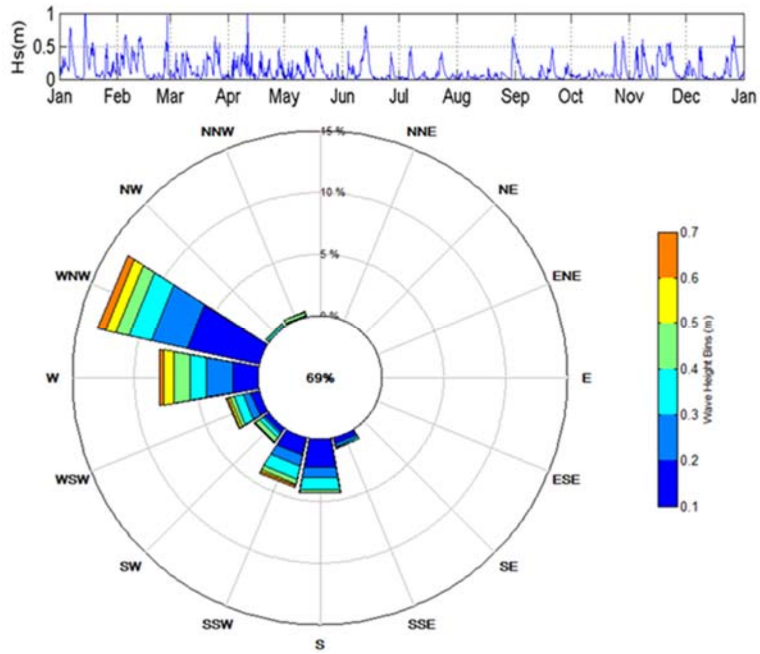

Figure 7 . 2006 wave record and wave rose showing an example of typical wave climate at Clam Pass

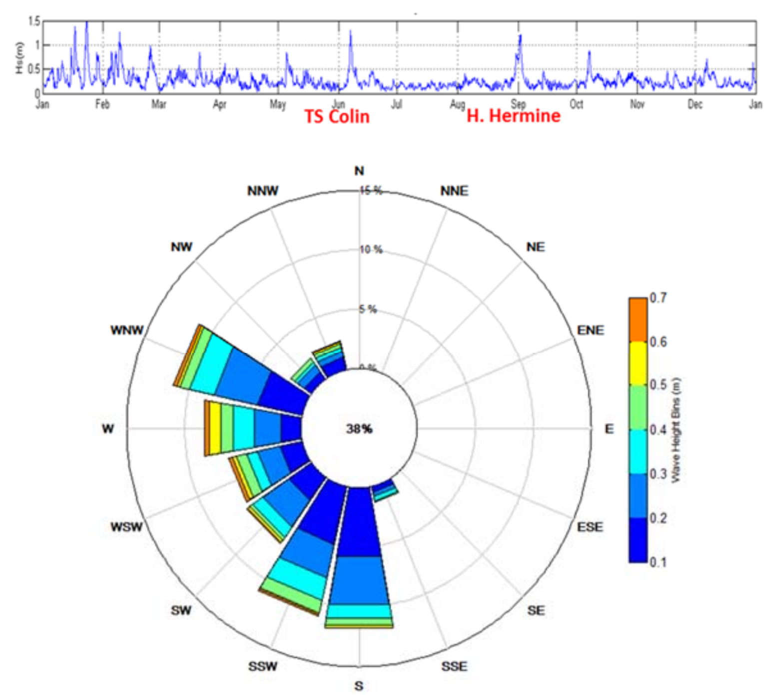

Figure 8 . 2016 wave record and wave rose showing effect of tropical storms on wave climate at Clam Pass

The analysis of the 13 year wave record indicated the atypical wave climate during 2016 and 2017 which included high tropical storm activities. **Figure 8** shows wave record and wave rose of 2016 indicating the effects of the tropical storms on wave energy and direction. The figure indicates that during 2016, calm waves conditions represented only 38% compared to over 60% of the time typically. The 2016 wave events included significant wave energy from south and southwest directions in addition to the northwest waves during winter months.

2.3 Wave climate variability and maintenance dredging

The shoreline change model ONELINE (Dabees and Kamphuis, 1998) was used to simulate potential annual sediment transport at Clam Pass for each year of the 13 year record. The model uses the hourly wave record and calculates potential sediment transport based on wave conditions, beach orientation, beach slope and sediment grain size. Using the full wave record allows for considerations of seasonal variations and annual variation of wave climate. In addition to estimation of potential net sediment transport, this approach also allows quantification of the southbound and northbound sediment transport components and annual variability in the distribution of north and south sediment transport.

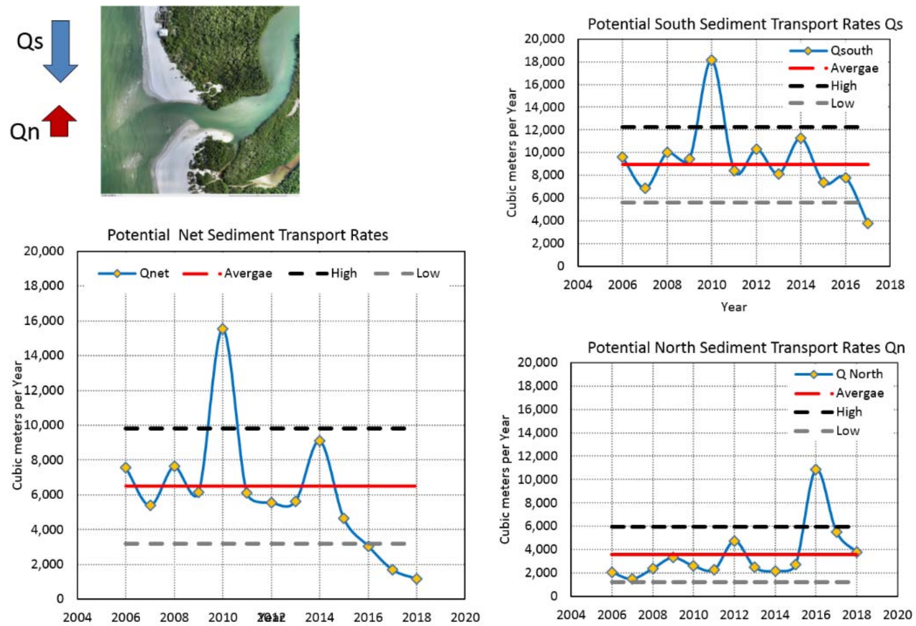

Figure 9 . Calculated net, north and south annual sediment transport rates at Clam Pass based on wave driven sediment transport modeling for wave record of 2006 to 2018

Figure 9 shows the calculated annual north, south and net sediment transport rates. The figure shows the model computation for each year of the 13-year record and indicates the potential average, high and low expected yearly range based on the modeled period. **Figure 10** shows the calculated annual gross sediment transport which is the magnitude total of both north and south transport, and indication of total energy regardless of direction. While the net transport is commonly used to evaluate sediment budgets for open coasts, the gross sediment transport is an important measure of wave energy and sediment transport in areas near inlets where the inlet channel or dredged areas act as a sink for sand transported from both directions. The sediment transport figures show the yearly variations in sediment transport magnitudes and breakdown between north and south sediment transport components.

Wave events and tropical storms in 2010, 2012, 2016 and 2017 influenced the overall sediment transport magnitudes and directions. In 2012 the Passage of Tropical Storms Debby and Isaac caused significant shoaling at the inlet mouth and the pass was eventually closed in the fall of 2012. In 2016 and 2017 the net sediment transport was to the north which is opposite to the typical yearly trend.

Figure 11 shows the yearly ratios of north and south bound transport relative to total yearly sand transport. Long-term averages indicate that in most years the majority (~80%) of wave energy drives sand transport alongshore from north to south. In 2016 and 2017 the majority of wave energy came from the southwest driving sand transport towards the north which is opposite of the predominant trend.

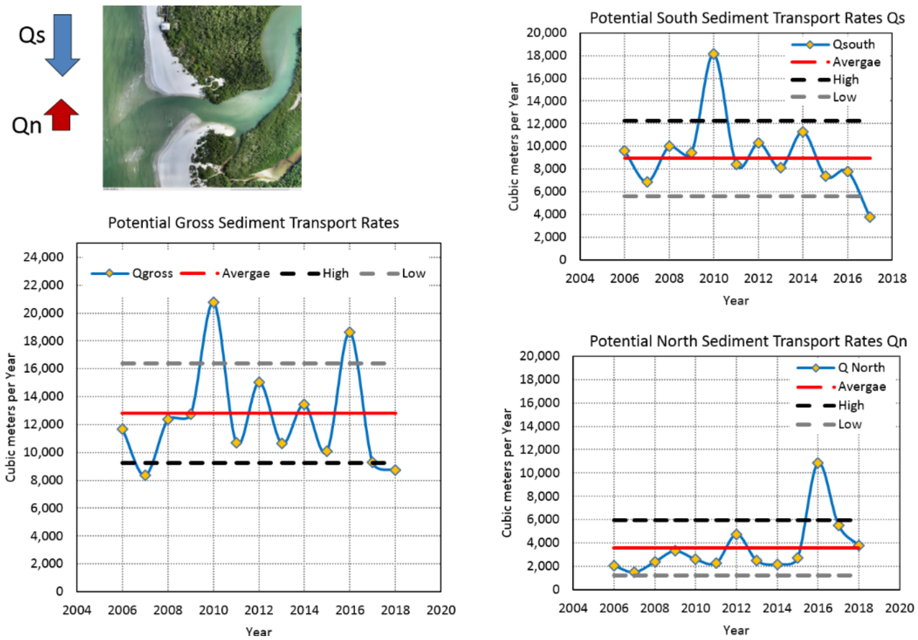

Figure 10 . Calculated gross, north and south annual sediment transport rates at Clam Pass based on wave driven sediment transport modeling for

Following the maintenance dredging of April 2016, the inlet was impacted by tropical storms Colin and Hermine in the fall of 2016 as well as active winter storms and tropical storm Cindy in 2017. The 2016 maintenance dredging of Clam Pass placed approximately 15,000 cubic yards south of Clam Pass in April, and in December 2016 beach nourishment along Park Shore beach south of Clam Pass Park beach added 32,000 cubic yards.

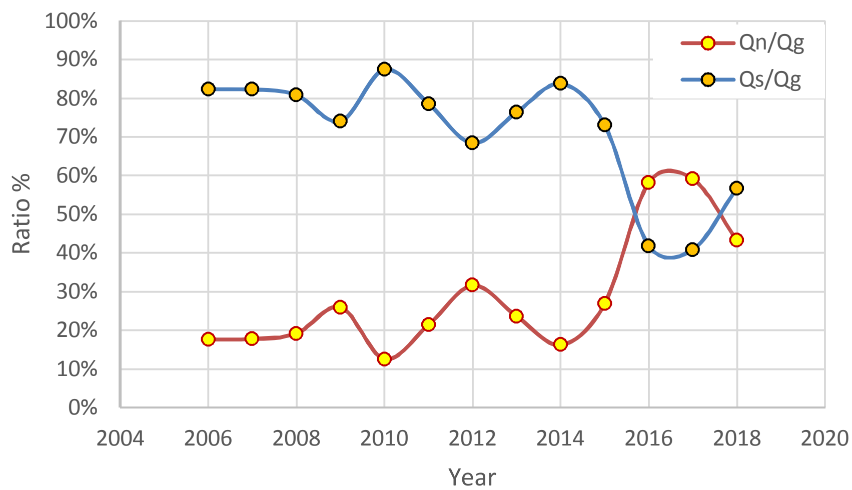

Figure 11. Ratios of north transport 'Qn' and south transport 'Qs' to total 'Qgross' transport

The sand placement south of the inlet and sequence of wave events pushed sand towards the inlet causing significant inlet migration northward and sand spit growth across the inlet mouth. Emergency maintenance excavation of the inlet channel and grading of the inlet banks was completed in July 2017 to restore the inlet stability and avoid potential of inlet closure. **Figure 12** shows pre and post inlet channel restoration in July 2017.

Later in 2017 Hurricane Irma which made landfall in Collier County influenced the water levels and morphology of Clam Pass. While Hurricane Irma was a major hurricane with direct impacts on Collier County, the inlet channel restoration before Irma may have helped prevent Clam Pass from closure. However, Clam Pass exhibited more significant morphologic response to Hurricane Irma than larger inlets in the region. Hydrodynamic forcing due to changes in water levels provided enough flow through the inlet to maintain such a small inlet open. Water levels fluctuation exceeding 8 feet range in a system where the astronomical tide is less than 3 feet on an average tide. During the storm, strong current due to rapid change in water levels maintained flow channeling through wave driven sand deposition in the inlet channel and flood shoal areas. The morphologic response to these processes included migration and meandering channels that scoured around the deposition areas.

Figure 12 . Pre and Post construction for the 2017 Clam Pass inlet channel restoration

The 2018 wave energy also indicated increased energy from the south than average such that the net transport was relatively small due to the similar magnitude of north and south transport in 2018. Maintenance dredging in 2018 was completed to restore the inlet to design template including hydraulic dredging of the interior flood shoal areas and correct the inlet channel meander. The 1-year post dredging survey indicated the inlet remains in stable conditions. **Appendix A** includes the 2019 monitoring data and comparative plots at various monitoring stations. **Figure 13** is an aerial photo of July 2019 showing the condition of the inlet and adjacent beaches 1 year post the 2018 maintenance dredging.

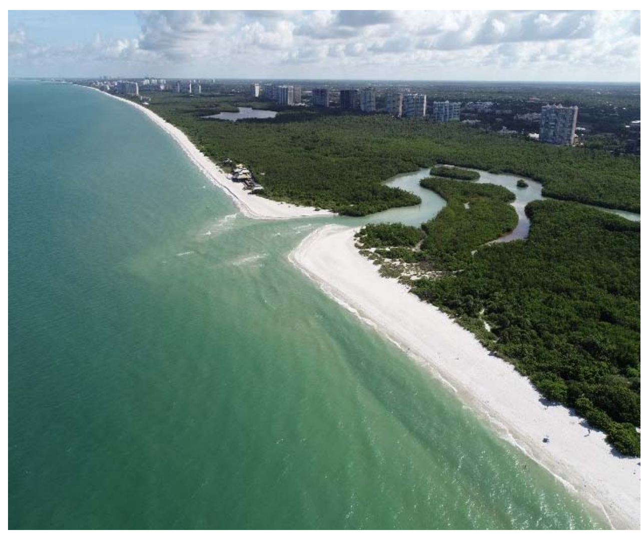

Figure 13 . July 2019 conditions at Clam Pass (1-year Post construction of the 2018 Clam Pass maintenance dredging)

2.4 Timeline of Dredging Events and Tropical Storms at Clam Pass

The analysis of the wave record presented in this study provided the timeline of storm activities and recent inlet dredging events as shown in **Figure 14**. The figure highlights named storms that had significant impacts on southwest Florida in general and Clam Pass in particular.

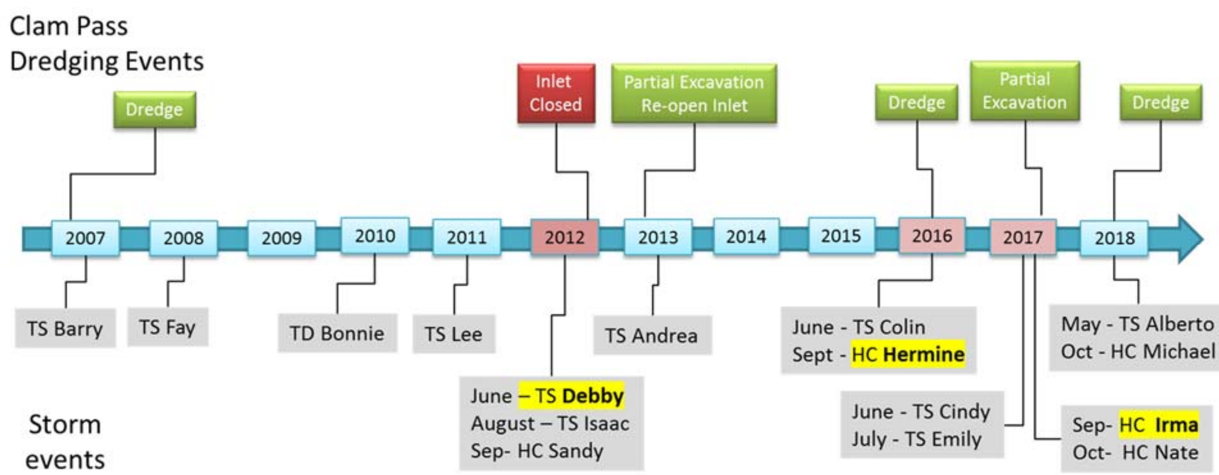

Figure 14 . Timeline of tropical storms and dredging events (2007-2018)

The analysis of the wave record and storm events indicates the correlation between increased storm activities and dredging events. Storm activity affected southwest Florida in 2012, 2016 and 2017. The inlet closed in the fall of 2012 following sequence of tropical storms Debby, Isaac and Sandy. Emergency maintenance in 2017 and maintenance dredging in 2018 helped avoid inlet closure during the active years of 2016/2017 and restored the inlet to stable conditions.

This illustrates the importance of the monitoring program and the ability to conduct emergency responses in a timely manner following major storm events to avoid potential for inlet closure. The wave analysis also provided assessment of the variability in long-term wave climate and the inlet response to prevailing sediment transport in both directions. Typically the beach and inlet geometry adjusts to near equilibrium following long-term trends. This includes the predominant trends of sand transport from north to south. Sustained wave energy from the south over two consecutive years represented atypical conditions that impacted inlet stability and required maintenance dredging to restore the inlet stability.

This analysis also indicates the critical nature of Clam Pass as small inlet that is stable under typical conditions and requires maintenance dredging to restore inlet stability when sever weather and tropical storms impacts the inlet. The inlet stability is event driven, and the maintenance dredging helps improve the inlet resiliency and avoid inlet closure.

3. Inlet Dredging Cost Analysis

As discussed above, Clam Pass is a small inlet and requires maintenance dredging to maintain the health of the Clam Bay ecosystem and avoid potential for inlet closure. The inlet has been dredged a total of 7 times since the development of the initial NRPA management plan in 1998. The dredging template and methods of dredging varied depending on conditions and timing of each event. **Table 2** provides listing of dredging information and costs for each of the 7 events. The record indicates that 5 dredge events used hydraulic dredging equipment which enables dredging the entire dredging template including the interior flood shoal areas. Two events in 2013 and 2017 were limited to mechanical excavation equipment which included partial dredging of the template limited to the inlet channel and small part of section B of the flood shoal area. The limited excavation by mechanical equipment provided cost effective and rapid response to emergency conditions following inlet closure in 2012 and to avoid inlet closure in 2017.

Table 2 Details of dredging events information and costs for Clam Pass

Year		*Pay Quantity (includes grading) (cy)*	*Total Volume (includes grading) (cy)*	*Section A Dredge Width (feet)*	*Dredge Depth (feet)*	*Equipment*	*Construction Cost* based on bid tabulation	*Construction equivalent Cost (2018 $)*
	A				-5.0 NGVD			
1999	B		32,000	30	-4.0 NGVD	Hydraulic	$ 321,030	$ 484,755
	C				-4.0 NGVD			
	A	ND						
2002	B		11,725		-4.0 NGVD	Hydraulic	$ 162,125	$ 230,218
	C	ND						
	A				-5.5 NGVD			
2007	B		20,603	80	-4.5 NGVD	Hydraulic	$ 376,417	$ 455,465
	C				-4.5 NGVD			
2012	*Inlet Closes*							
	A	13,008			-5.8 NAVD			
2013	B	4,824	20,266	45	-5.3 NAVD	Mechanical	$ 233,411	$ 252,084
	C	2,434			-5.3 NAVD			
	A	9,366			-5.0 NAVD			
2016	B	3,368	18,987	50	-4.0 NAVD	Hydraulic	$ 469,000	$ 492,450
	C	6,253			-4.0 NAVD			
	A	10,994			-5.0 NAVD			$ 85,303
2017	B	ND	10,994	50	-4.0 NAVD	Mechanical	$ 82,818	
	C	ND			-4.0 NAVD			
	A	6,275			-5.0 NAVD			
2018	B	3,320	11,685	50	-4.0 NAVD	Hydraulic	$ 235,982	$ 235,982
	C	2,090			-4.0 NAVD			

* ND indicates no dredging occurred in this section.

As discussed in previous sections of this study, the inlet is critically stable under typical conditions and excessive shoaling is directly related to sequence and intensity of storms. The average interval between dredging events is 3 years. The largest interval between dredging events was 6 years between 2007 and 2013 which included inlet closure in 2012. Annualized cost over various time frames are shown in **Figure 15**.

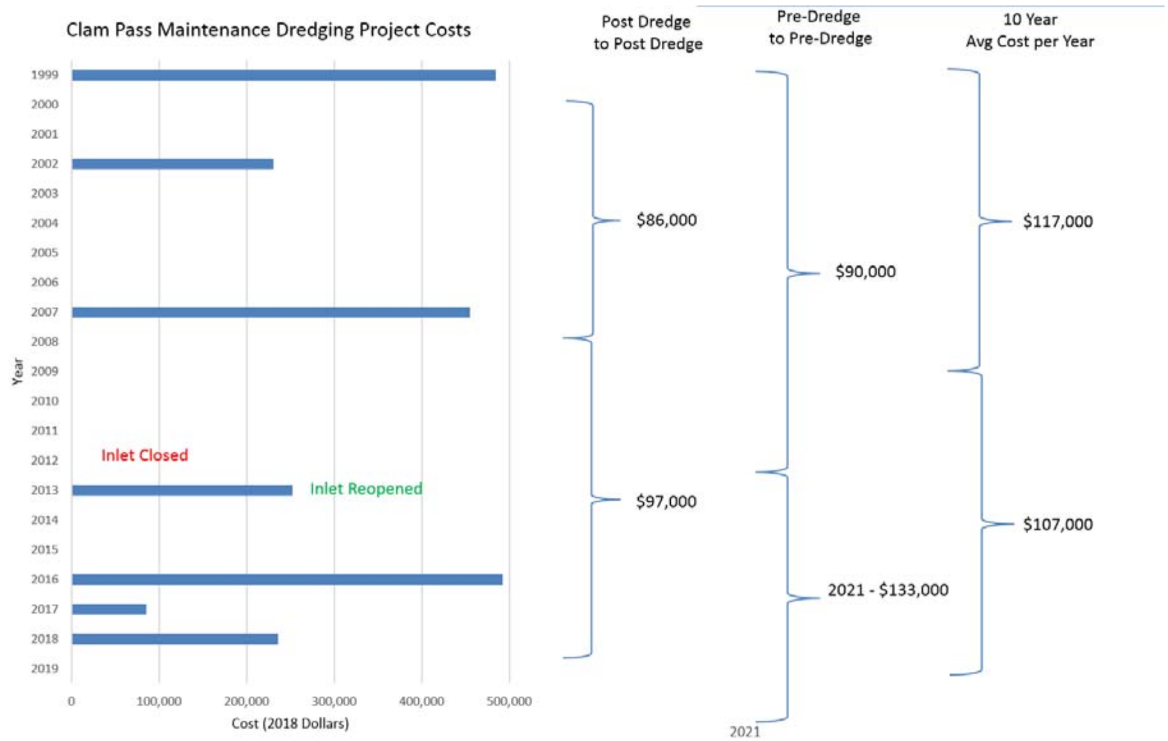

Figure 15 Annualized maintenance cost over various time frames.

Depending on the selected time frame the annualized dredging cost for Clam Pass at present time ranges between $97,000 and $133,000 per year. Over that 21-year period, Clam Pass cumulative dredging volume is approximately 126,000 cubic yards at a total cumulative cost of approximately 2.3 million dollars. This represents an annual equivalent cost of dredging 6,000 cubic yards per year is $106,000 dollars over the past 21 years.

4. Review of Regional Inlets

A review of maintenance dredging record of regional small inlets was completed as part of this study. **Figure 16** shows the selected inlets of Doctors Pass, Clam Pass, Wiggins Pass and Blind Pass (Lee County). While all these inlets are located in southwest Florida and considered as small inlets, Clam Pass is the smallest open inlet in the region. The Figure includes a plot of the cumulative dredging volume and dredging events for each inlet. The figure illustrates the small size of Clam Pass compared to other inlets. The figure also indicates that all inlets in this system were dredged between 3 to 5 times in the last 10 years. Clam Pass was dredged 4 times during the past 10 years including two partial excavation events. The analysis of dredging volumes and events indicates that Clam Pass maintenance dredging volumes and costs are among the smallest in the region for maintenance dredging. It is important to note that each inlet has different physical conditions and various objectives for maintenance dredging.

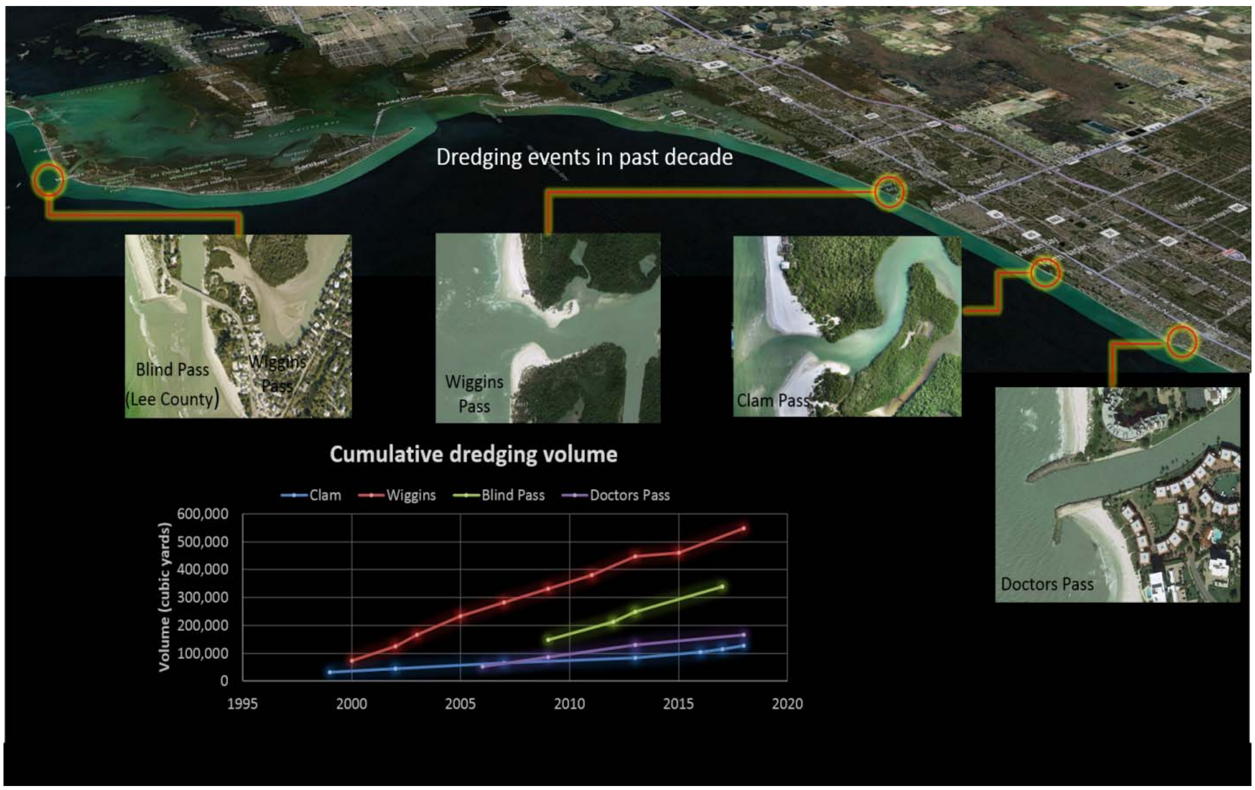

Figure 16. Cumulative dredging volumes over the past 20 years for small inlets in southwest Florida

5. Review of Inlet Management

5.1 Inlet Channel

The 2014 updated management plan evaluated the dredging template for the 4 dredging events prior to 2014 as well as goals and objectives stated by various stakeholders. The 2014 plan presented minor modifications to the dredging template to improve the inlet stability and minimize potential impacts to the ecosystem. These included:

- Modification of the inlet channel cross section to reduce channel bottom width and include large tidal flats and gradual grading of inlet banks to mimic natural conditions while maintaining equilibrium area of flow. **Figure 17** shows illustration of the typical channel cross section used in the current dredging template compared to the 2007 dredging template.
- Slight reduction of dredging depth to avoid and minimize potential of dredging cohesive sediment or non-beach compatible sediment.
- Provide small buffer between the active dredging areas and mangrove shoreline to minimize potential impacts to mangroves.

The above minor modifications were designed to promote inlet stability and address environmental concerns. The overall change in the capacity of the dredging template was less than 10% of the template capacity used in the 2007 dredging. For example, the total volume for 2007 and 2016 dredging was approximately 21,000 and 19,000 respectively.

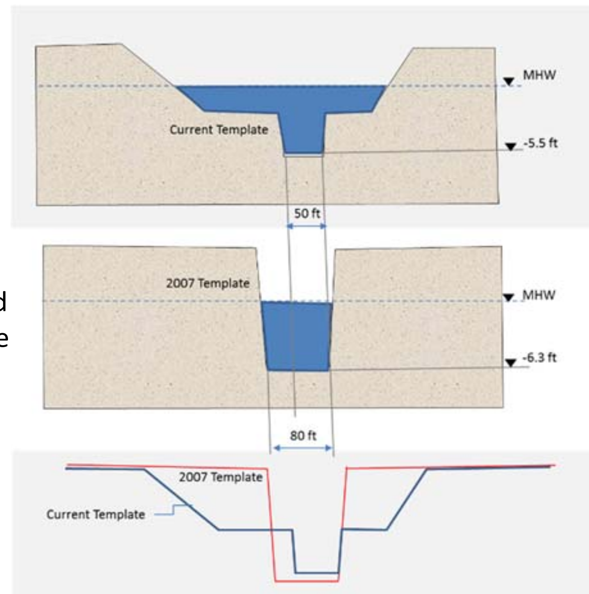

Figure 17 . Typical maintenance dredging cross section in the 2007 template and current permitted template.

5.2 Adjacent Beach Width

A review of beach width north and south of the inlet indicated that in general the beach width north of the inlet is significantly wider than the beach south of the inlet. This in part in response to the effect of the typically predominant transport in this region from north to south and the active beach nourishment program. **Figure 18** shows the beach width north and south of Clam Pass between 2005 and 2019. The figure indicates that on average the beach north of Clam Pass is approximately 50 feet wider than the beach south of the inlet. This offset in beach width makes the inlet more

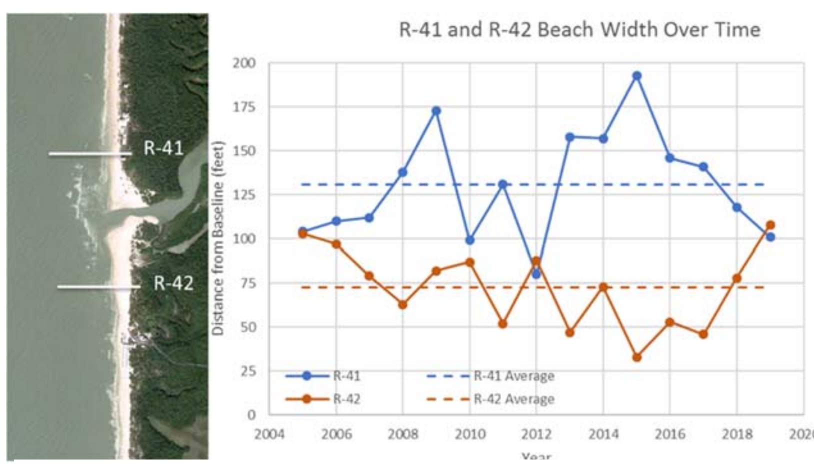

Figure 18 . Beach width north and south of Clam Pass (2005-2019)

resilient to storms originating from the north than storms originating from the south. This offset in beach width and shoreline position across the inlet is among the reasons why the inlet was impacted significantly in years with tropical storm activities from the south such as 2016/2017 season. Sand placement from the inlet maintenance in 2016 and beach nourishment later the same year south of the pass were followed by very active wave events driving sand northward towards the inlet and forming large sand spit across the inlet mouth. Emergency restoration of the inlet channel was done following tropical storm Cindy in the summer of 2017.

5.3 Inlet Management Program

The hydraulic stability of Clam Pass extends beyond the inlet channel and includes the ebb shoal and flood shoals. The 2014 management plan provided monitoring criteria that includes hydraulic and physical monitoring to help identify critical conditions at various parts of the inlet system. The monitoring program includes the following:

- Real time monitoring of hydraulic efficiency of the inlet based on 4 water level gauges in the bay system.
- Monthly observation of inlet through aerial photograph, and monthly records of bay tidal range
- Annual physical monitoring survey to assess inlet conditions and quantify shoaling areas within the maintenance dredging template

Monitoring and observation of the morphologic changes indicated when maintenance dredging was recommended and when emergency dredging was necessary to restore inlet stability and avoid inlet closure.

5.4 Long term Morphologic Change Trends

The Clam Pass management and monitoring program identified long-term changes and trends including the following :

- The collapse of the ebb shoal following inlet closure in 2012 deposited large amount of sand at the inlet mouth. The lack of established or mature ebb shoal complicated the inlet reopening and recovery of the ebb shoal. This increased the inlet vulnerability to storms while ebb shoal delta was developing and natural sand bypassing established.
- Erosion of the south bank mangrove shoreline in the flood shoal area started near the east end of the inlet channel since inlet dredging in 1999, and progressed eastward along the south bank of the flood shoal area resulting in progressive widening of section B over time.
- The south bank erosion became more progressive in the flood shoal in section B due to lack of dredging between 2007 and 2013 and wave events of 2010 and 2012. This resulted in change in flow patterns within the flood shoal area and increased meandering of the inlet channel. **Figure 19** shows the change in cross section area and southward migration of flood shoal channel between 2010 and 2014.

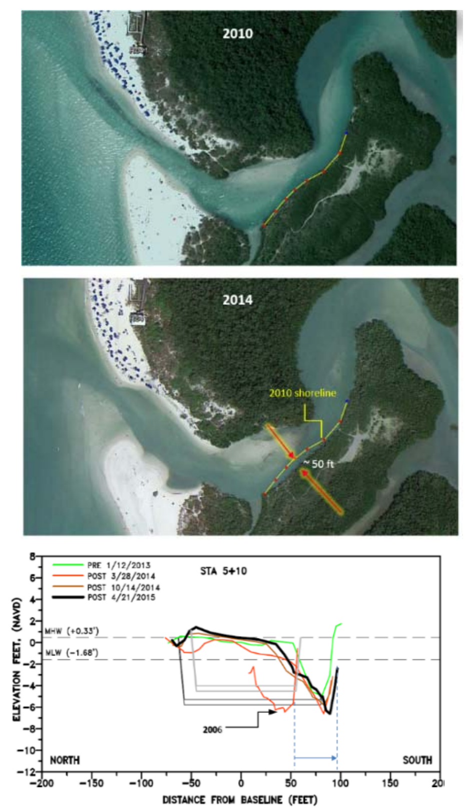

Figure 19 . Long term changes in flood shoal area (section B) 210-2014

The widening of section B of the flood shoal due to the south bank mangrove erosion altered the geometry and flow patterns in the flood shoal. This resulted in rapid shoaling in the central area of section B following maintenance dredging and sharp meander of the channel along the north inlet bank.

5.5 Adaptation and Management

The data analysis and development of the updated 2014 NRPA management plan highlighted the critical sensitivity to storm events and dynamics of the inlet channel. The design maintenance dredging plans included the design channel template described above and illustrated in **Figure 17**. The composite design section with wide tidal flat areas and grading zones on inlet banks allowed for more effective implementation to address changing inlet dynamics. The pre dredging inlet conditions over the three maintenance events under the current plan were starkly different due to significant change in wave climate and storm activities. The current permit authorization and grading areas allowed rapid response and restoration of inlet channel to design conditions in timely manner in spite of the large migration of inlet channel and sand spit formations away from the typical channel dredging template.

The impacts of Hurricane Irma on Clam Pass accentuated the trend discussed in the above section of the widening of section B and flow channelization along the south bank resulting in increased inlet channel meander and reduced inlet stability. During the 2018 maintenance dredging sand was placed with the south bank grading area to dyke the channel meander on the south bank. This allowed the flow to remain within the design template area and reduced the potential for inlet channel meandering. The 2019 monitoring survey indicated improved flow and reduced shoaling in section B of the flood shoal and improved sand bypassing patterns across the inlet. **Figure 20** show aerial photos of the May 2018 immediately post dredging conditions and July 2019 conditions 1 year post construction. The figure shows the stability of the inlet channel and inlet morphologic features and response to the adaption measures allowed by the inlet bank grading zone.

Figure 20. Clam Pass immediately post 2018 maintenance dredging and 1 year post construction conditions

The management efforts also included fulfillment of permit compliance items and permit updates through minor permit modifications. Few minor permit modifications were completed over the past 5 years to implement adaptation measures, allow for rapid emergency response and address sensitive environmental issues.

6. Summary of Findings and Recommendations

This study included review and analysis of available data and information related to Clam Pass and its maintenance dredging program. The data reviewed in this analysis included:

- 24 survey data sets covering the period from 1999 to 2019
- Annual aerial photos 2001 to 2019
- Adjacent beach profiles 2005-2019
- Wave data 2006 to 2018
- Dredging records on Clam Pass and other regional inlets

The study included analysis of the evolution of inlet morphology and effects of storm events and maintenance dredging on inlet stability. The study established a timeline of natural and engineering events.

6.1 Findings

The following list summarizes the general findings:

1. ***Clam Pass is a small inlet critically stable under typical conditions and vulnerable to storm impacts.***
   - Inlet shoaling is related to frequency, intensity and sequence of storm events and timing of maintenance dredging
2. ***Increased storm activity 2016/2017 including atypical sediment transport direction reversal impacted Cam Pass.***
   - Storm timeline correlates the frequency of storms with inlet shoaling and instability
   - The inlet is more vulnerable to large increase in sediment transport from the south
   - Beach width and shoreline position offset between beaches adjacent to the inlet increase inlet vulnerability to storms originating from inlet downdrift direction
3. ***Section B of the flood shoal has progressively widened over time, resulting in increased channel meander.***
   - Erosion of the south bank mangrove shoreline in the flood shoal area started near east end of inlet channel since inlet dredging in 1999, and progressed eastward along the south bank of flood shoal area resulting in progressive widening of section B over time.
   - The south bank erosion became more progressive in the flood shoal in section B due to lack of dredging between 2007 and 2013 and wave events of 2010 and 2012. This resulted in widening of section B, change in flow patterns within the flood shoal area and increased meandering of the inlet channel.
   - Meandering channel makes the inlet vulnerable especially to sediment transport from south and onshore movement in ebb shoal during storms.
   - Corrective measures to block flow through the marginal channel meander along the inlet banks helped improve the inlet stability post the 2018 maintenance dredging event.

4. ***The inlet maintenance template is governed by the bay system physical features/mangrove areas and tend to reach equilibrium rapidly post maintenance dredging.***
   - Post dredging average and minimum cross section areas of flow are consistent since 1999.
   - Inlet equilibrium conditions have a smaller flow area than previous or current dredge templates.
   - Dredging events are typically followed by a relatively rapid return to equilibrium condition.
   - Maintenance dredging is necessary when shoaling reach critical limits identified in the NRPA Management Plan

5. ***Annualized cost of inlet maintenance dredging are similar throughout two decades of maintenance.***
   - Maintenance costs in actual dollars and 2018 constant dollars are relatively similar for each of the past two decades.
   - Maintenance frequency is mostly governed by storm activities and other factors, such as adjacent beaches, inlet orientation, regulatory, environmental, and administrative considerations.

6.2 Recommendations

1. ***Continue to monitor inlet stability and recommend maintenance dredging when shoaling or hydraulic efficiency falls below critical limits.***
   - Maintain ability to implement rapid response to severe impacts due to storms is recommended to avoid potential for inlet closure

2. ***Continue with adaptative plans allowing for grading inlet banks to streamline flow and minimize channel meander.***
   - Continue to adjust grading area along both inlet banks to reduce potential for marginal channelization of flow
   - Consider extension of grading area into accessible stations of section B.
   - Monitor the resiliency of minimizing channel meanders through section B and consider alternatives to stabilize mangrove shoreline if regression continues.

3. ***Continued coordination with sand nourishment events.***
   - The timing and volume of beach nourishment in the disposal template of Clam Pass maintenance can be critical to inlet stability.
   - Coordination of sand placement and potential volume in the dredging template is necessary to enable adequate space in the template remains available to address the potential inlet impacts due to storms and unforeseen meteorological events.

7. References

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