Sebastian Inlet Sediment Budget: Technical Memorandum

Office of Resilience and Coastal Protection

Florida Department of Environmental Protection

March 2023

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Review of the Summer 2011-2021 Sediment Budget

In the last technical advisory committee (TAC) meeting on August 24th, 2022 for Sebastian Inlet, two principal sediment budgets, namely a unicellular budget and bifurcated budget, were presented by Dr. Zarillo. The unicellular budget uses computational cells encompassing both the beach-dune and offshore whereas the bifurcated budget uses two cross-shore computational cells, the beach-dune and nearshore down to ~-20 ft NAVD88 as well as offshore cells from ~-20 to -40 ft NAVD88. The timeframe of the budgets comprises the last decade of bathymetric data at Sebastian Inlet from summer 2011 to summer 2021. The spatial domain of the budgets includes Brevard County R-189 to R-219 and Indian River County R-1 to R-30.

The unicellular sediment budget (**Figure 1**) contains nine cells in total, four on both the north and south sides of the inlet as well as a single inlet cell which encompasses both the ebb and flood shoals. The cells reach a maximum depth of -40 ft NAVD88. In cells S3 and S4, the placement volumes of 21,280 cy/yr and 26,659 cy/yr, respectively, are ejected from the system into the offshore to represent offshore-directed transport and loss of sediment from the coastal littoral system. **Equation 1** illustrates the calculation of the target bypassing objective for the unicellular sediment budget is provided below (see Appendix A for contextual information regarding the derivation of the inlet target bypassing objective). Using Equation (iii) from Appendix A:

Equation 1:

$$\boldsymbol{T} = \sum (\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P})_{\boldsymbol{Updrift;Ebb\ Shoal;Channel;Flood\ Shoal}}$$

$$\boldsymbol{T} = [\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P}]_{\boldsymbol{N4+N3+N2+N1}} + [\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P}]_{\boldsymbol{Inlet\ Cell}}$$

$$\boldsymbol{T} = [((\mathbf{1752} + \mathbf{12095} + \mathbf{2996} + \mathbf{10448}) - (\mathbf{1572} + \mathbf{1493} + \mathbf{1493} + \mathbf{1022})]_{\boldsymbol{N4+N3+N2+N1}} + [\mathbf{7162} + \mathbf{11120}]_{\boldsymbol{Inlet\ Cell}}$$

$$\boldsymbol{T} = [\mathbf{21711}]_{\boldsymbol{N4+N3+N2+N1}} + [\mathbf{18282}]_{\boldsymbol{Inlet\ Cell}}$$

$$\boldsymbol{T} = \mathbf{39,993}\ \boldsymbol{cy/yr}$$

***Figure 1**: Dr. Zarillo's Summer 2011-2021 unicellular sediment budget including placement (P) and removal (R) volumes per cell. Blue and red cells correspond with accretion and erosion respectively.*

The bifurcated sediment budget (**Figure 2**) contains nineteen cells in total, eight on both the north and south sides of the inlet as well as three inlet cells consisting of the flood shoal, upper ebb shoal, and lower ebb shoal. The eight cells on each side of the inlet were constructed by dividing the northern and southern cells from the unicellular budget into upper and lower subdivisions along the -20 ft contour.

Notably, the sum of the ΔV values in the bifurcated budget for the upper and lower cells as well as the three inlet cells do not equal their counterparts in the unicellular budget. As a result, the target bypassing objective obtained from this budget deviates from that of the unicellular budget. **Equation 2** illustrates the calculation of the target bypassing objective for the bifurcated sediment budget is provided below (see Appendix A for contextual information regarding the derivation of the inlet target bypassing objective). Using Equation (iii) from Appendix A:

Equation 2:

$$T = \sum (\Delta V + |R| - P)_{Updrift;Ebb\ Shoal;Channel;Flood\ Shoal}$$

$$T = [\Delta V + |R| - P]_{N4+N3+N2+N1} + [\Delta V + |R| - P]_{In.A} + [\Delta V + |R| - P]_{In.B} + [\Delta V + |R| - P]_{In.Interior}$$

$$T = [(((17955 - 10669) + (8750 + 2642) + (5102 + 2318) + (1271 + 10214)) - (1572 + 1493 + 1493 + 1022))]_{N4+N3+N2+N1} + [-5915]_{In.A} + [41636]_{In.B} + [-31952 + 11120]_{In.Interior}$$

$$T = [32003]_{N4+N3+N2+N1} + [-5915]_{In.A} + [41636]_{In.B} + [-20832]_{In.Interior}$$

$$T = 46{,}892\ cy/yr$$

***Figure 2**: Dr. Zarillo's Summer 2011-2021 bifurcated sediment budget including placement (P) and removal (R) volumes per cell. Blue and red cells correspond with accretion and erosion respectively.*

2011-2021 Sediment Budget: Outstanding Questions and Concerns

This memorandum seeks to address questions outlined across the three TAC meetings regarding the Sebastian Inlet sediment budgets presented in Figures 1 and 2. The following provides a summary of the primary concerns thus far.

1) Neither the unicellular nor bifurcated sediment budget has been adequately balanced. Both budgets possess unattributed residuals when the cell volumetric changes and sediment transport fluxes are entered into SBAS.

2) Both sediment budgets incorporate offshore transport in cells S3 and S4 to reduce the value of the flux exiting the littoral system. It has been suggested that the inlet system is losing significant volumes of sediment, potentially from storm-induced offshore transport, variation in Gulf Stream current velocity and sea level rise, the ebb jet of the inlet, or other analogous processes. Is sand being lost from the system and, if so, how much?

3) The ΔV values for the unicellular sediment budget in Figure 1 differ from the sum of their bifurcated equivalents in Figure 2.

4) The inlet interior exhibits a ΔV of -31,952 cy/yr (-11,120 cy/yr from removal), implying that the flood shoal, after accounting for sediment removal, is losing volume. This behavior is inconsistent with the fundamentals of inlet geomorphology in which the inlet acts as a sink for sediment.

To resolve the above questions, the Coastal Engineering & Geology Group (CEG) conducted a quality assurance analysis of the work presented on the summer 2011 to summer 2021 sediment budgets. The following section outlines the methodology used to reconstruct the unicellular sediment budget from the raw data shared via fellow TAC associates. The subsequent section concludes with the final results as well as a discussion of the potential paths forward.

Data and Methodology

This section provides an overview of the procedures used to process the data collected at Sebastian Inlet for incorporation into the sediment budget. The first subsection describes how the bathymetric data was used to quantify volume changes in the cells of the sediment budget. The second subsection describes how the sediment nourishment and removal volumes were proportionally allocated to the various cells. The methodology is presented in a step-by-step format to ensure replicability of the results.

Bathymetric Change Data

Several steps were involved in processing the bathymetric survey data prior to incorporation into the sediment budget. The data was downloaded from the Sebastian TAC Sharepoint site for analysis in ArcGIS Pro. Point shapefiles representing bathymetric survey data from summer 2011 and 2021 were imported alongside Dr. Zarillo's unicellular and bifurcated sediment cell geometries.

First, the "Create TIN" tool from the 3-D Analyst toolbox was used to create two TIN (triangular irregular network) surfaces, one representing the bathymetry of Sebastian Inlet in summer 2011 and the other representing the equivalent for summer 2021 (**Figure 3**: Top → Middle). The summer 2011 and 2021 point survey shapefiles were used as the input feature class for each respective simulation. The height field was set to "Z" and the Type was set as "Mass Points".

Next, the two TIN surfaces were clipped to the extent of the unicellular *Cell Geometries* feature class polygon (**Figure 3**: Middle → Bottom). However, before this could be done, pre-processing of the *Cell Geometries* polygon was required. First, a copy of the *Cell Geometries* layer was created using the "Copy Features" tool from the Data Management Toolbox. Then, the "Merge" tool within the Modify Features pane was used to merge the cells until the *Cell Geometries Copy* was a single, continuous polygon with no cell subdivisions.

The "Edit TIN" tool from the 3-D Analyst toolbox was used to clip each of the two newly created TINs to the extent of the polygon with no subdivisions. In each usage, the Input Feature Class was set as the *Cell Geometries Copy* polygon and the Type was set as "Hard Clip".

The steps detailed above resolved the discrepancy between the ΔV values of the unicellular and bifurcated sediment budgets, as the TINs downloaded from the Sharepoint which were utilized in the previous memorandum suffered from the same issue.

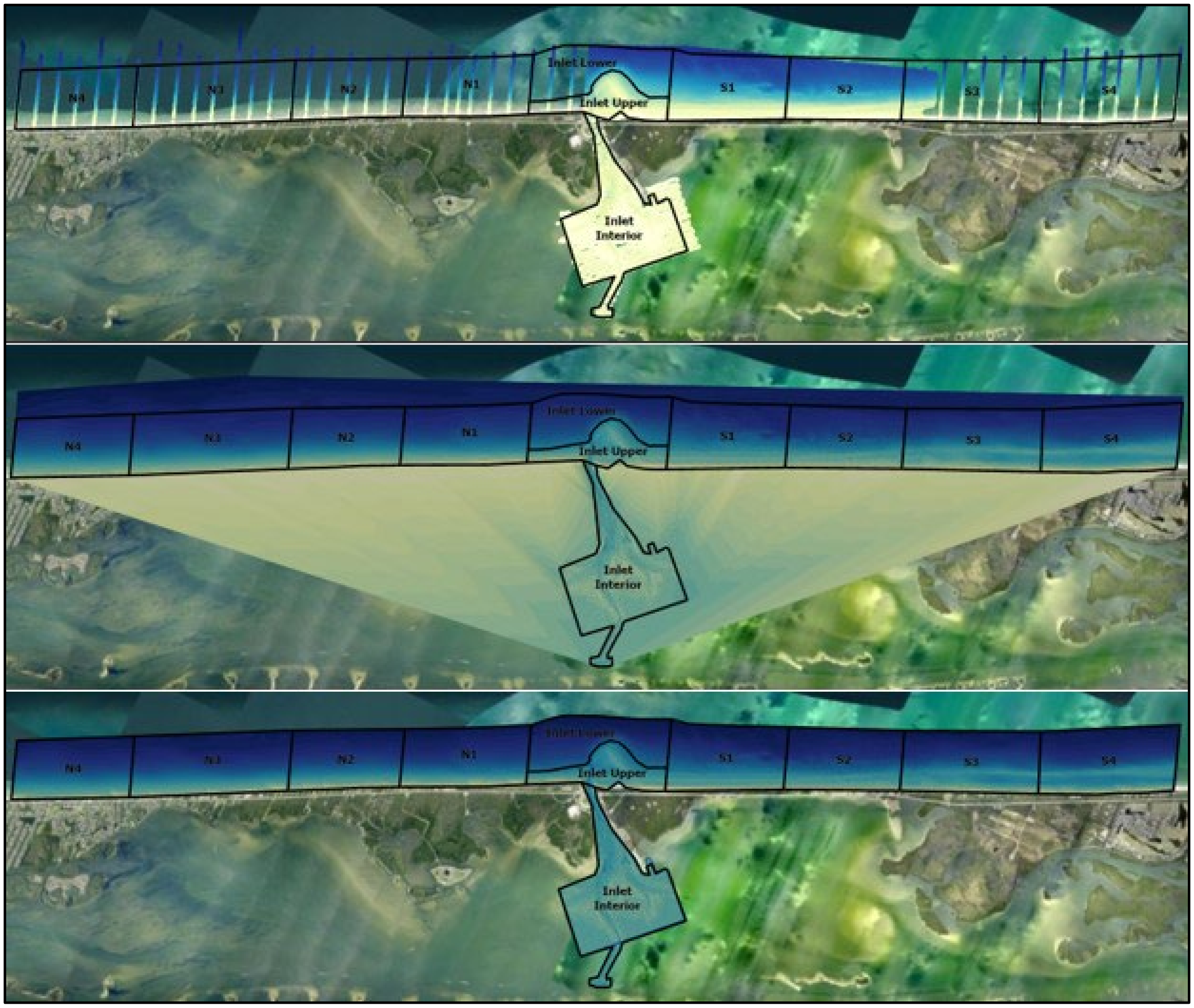

Figure 3: *Processing of Summer 2011 bathymetric data with superimposed sediment cell geometries at Sebastian Inlet. Darker colors correspond with increasing depth.*
Top: Summer 2011 bathymetric survey point data.
Middle: Summer 2011 TIN surface prior to clipping.
Bottom: Summer 2011 TIN surface post-clipping to the extent of the cell geometries.

After the 2011 and 2021 TINs were created and clipped, the volume changes per cell were computed. Three new fields were created within the attribute table of the *Cell Geometries* polygon feature class: “Plane”, “Volume”, and “SArea”. “Plane” represents the elevation from

which to compute the volume of sediment. "Volume" and "SArea" represent the volumes and surface areas calculated relative to said elevation, respectively.
Next, the "Polygon Volume" tool from the 3D Analyst toolbox was used to compute the volume for each individual sediment budget cell. This tool does not return an output but rather populates the "Volume" and "SArea" fields defined in the previous step. The tool was run twice, first using the *Summer 2021 TIN* bathymetry as input followed by the *Summer 2011 TIN*. The *Cell Geometries* feature class was used as the only input feature and defined the cell areas in which to compute the volume. Finally, the height of the reference place was set to correspond with the "Plane" field and the volume was calculated above the plane. In the *Cell Geometries* attribute table, -43.75 ft was assigned as the value for the "Plane" field for every sediment cell prior to running the tool. This depth was assigned as it is slightly deeper than the deepest recorded elevation between the *2021* and *2011 TIN* surfaces. Using a reference plane elevation deeper than the maximum of the two surfaces ensured that the ΔV computations were applied on surfaces of equivalent geometry. This is in opposition to the utilization of a shallower reference plane, which would differentially intersect the two surfaces and yield incompatible geometries for volumetric comparison. In addition, this enabled the utilization of all available survey data within the bounds of the sediment budget cells. The utilization of -43.75 ft for the reference surface by FDEP is the only difference in the volume calculation from that used by Dr. Zarillo in which -40.0 ft was used.

After the volumes of both the 2021 and 2011 surfaces were computed for each cell, the differences between the volumes within each respective cell was obtained. The total volume difference was converted to cubic yards and divided by 10 years to provide an annualized estimate of volume change.

Placement and Removal Data

Data consisting of placement and removal volumes within the coastal domain of the Sebastian Inlet sediment budget were provided by Brevard County, Indian River County, and the Sebastian Inlet District. Only placement and removal events which occurred between summer 2011 and summer 2021, namely the timeframe which coincides with that of the sediment budget, were included in the following analysis. For Brevard County, five distinct nourishment events were documented from 2011-2021, placing a total of 108,010 cy of sediment across cells N4, N3, N2, and N1 over the ten-year period. **Table 1** documents said nourishment events:

Table 1: *Historical nourishment volumes within the northern domain of the Sebastian Inlet sediment budget from 2011-2021. Data provided by Brevard County.*

Date	Total Placement [cy]	Placement Location
Jan-Apr 2014	2,905	R-189 to R-200
Jan-Mar 2017	30,040	R-189 to R-213
Dec-Apr 2018	30,486	R-189 to R-213
Dec-Apr 2020	30,793	R-189 to R-213
Dec-Feb 2021	13,786	R-189 to R-199

To determine the total volume of placement in each cell north of the inlet, placement volumes per event were proportionally allocated to their respective cells under the assumption that the nourishment volumes were evenly distributed across their spatial domain. In other words, for the first placement event which, in 2014, placed 2,905 cy between R-189 and R-200, this volume was divided between cell N4, which spans from R-189 to R-195, and cell N3, which spans from R-195 to R-203. The nourishment volume of 2,905 cy was placed across a total of eleven range monuments, six of which are in N4 and five of which are in N3. Therefore, the volumes are proportionally allocated in accordance with the following calculations:

$$\mathbf{2,905\ cy * \frac{6}{11} = 1,585\ cy\ in\ N4}$$

$$\mathbf{2,905\ cy * \frac{5}{11} = 1,320\ cy\ in\ N3}$$

The results of these calculations for each placement event are shown below in **Table 2**. The table also displays the total cubic yards of sediment placement per cell from 2011-2021 as well as the annualized placement in cubic yards per year (obtained simply by dividing the total by the ten-year interval of the sediment budget).

***Table 2**: Historical nourishment volumes within the northern domain of the Sebastian Inlet sediment budget from 2011-2021, proportionally allocated per sediment cell. Total and annualized quantities are also provided.*

Date	N4 (R-189 to R-195)	N3 (R-195 to R-203)	N2 (R-203 to R-209)	N1 (R-209 to R-216)
Jan-Apr 2014	1585	1320	-	-
Jan-Mar 2017	7510	10013	7510	5007
Dec-Apr 2018	7622	10162	7622	5081
Dec-Apr 2020	7698	10264	7698	5132
Dec-Feb 2021	8272	5514	-	-
Total [cy]	32686	37275	22830	15220
Annualized [cy/yr]	3269	3727	2283	1522

The methodology detailed above for the north side of the inlet was replicated using the placement and removal volumes obtained from the Sebastian Inlet District (SID) and Indian River County (IRC) for 2011 to 2021. This data covers the shorelines to the south of the inlet as well as the inlet interior cell which includes the sand trap and flood shoal. Overall, 778,049 cy were placed across the southern cells (S1, S2, S3, and S4) and 468,060 cy were removed from the inlet interior cell within the ten-year timeframe. The raw data is presented below for SID and IRC in **Table 3** and **Table 4**, respectively. Then, in **Table 5**, the total and annualized volumes per cell are provided.

***Table 3**: Sebastian Inlet District data depicting placement and removal volumes within the Sebastian Inlet interior and southern domain of the sediment budget from 2011-2021.*

Year	Total Placement [cy]	Placement Location	Total Removal [cy]	Removal Location
2011/2012	119,900	R-6 to R-17	141,300	Inlet Interior
2012/2013				
2013/2014	34,600	R-6 to R-17	-	-
2014/2015	111,200	R-6 to R-17	160,500	Inlet Interior
2015/2016	55,800	R-6 to R-17	-	-
2016/2017				
2017/2018	30,700	R-6 to R-17	-	-
2018/2019	113,570	R-10 to R-17	166,260	Inlet Interior
2019/2020				
2020/2021	59,925	R-10 to R-17	-	-

Table 4: *Indian River County data depicting placement volumes within the southern domain of the sediment budget from 2011-2021.*

Date	Total Placement [cy]	Placement Location
2012	85,919	R-20 to R-26.5
2014/2015	35,975	R-24 to R-30
01/2021-04/2021	130,460	R-24 to R-30

Table 5*: Historical placement and removal volumes within the inlet interior and southern domain of the Sebastian Inlet sediment budget from 2011-2021, proportionally allocated per sediment cell. Total and annualized quantities are also provided.*

Data Source	Date	S1 (R-4 to R-10)	S2 (R-10 to R-16)	S3 (R-16 to R-23)	S4 (R-23 to R-30)	Inlet Interior
SID	2011/2012	43600	65400	10900	-	-141300
	2012/2013					
	2013/2014	12582	18873	3145	-	-
	2014/2015	40436	60655	10109	-	-160500
	2015/2016	20291	30436	5073	-	-
	2016/2017					
	2017/2018	11164	16745	2791	-	-
	2018/2019	-	97346	16224	-	-166260
	2019/2020					
	2020/2021	-	51364	8561	-	-
IRC	2012	-	-	39,655	46,264	-
	2014/2015	-	-	-	35,975	-
	01/2021-04/2021	-	-	-	130,460	-
Total [cy]		128,073	340,819	96,458	212,699	-468,060
Annualized [cy/yr]		12,807	34,082	9,646	21,270	-46,806

In summary, both the former and updated annualized placement and removal volumes per sediment cell are included in **Table 6**. The updated values were revised and verified by both FDEP and Dr. Zarillo. Please note that several substantial differences exist between the updated volumes and those presented in the sediment budgets in Figures 1 and 2. In particular, the removal volume from the sediment impoundment basin and channel is substantially greater in magnitude (-46,806 cy/yr vs -11,120 cy/yr), thereby better explaining the volume changes of the inlet's flood shoal.

Table 6: *Former and updated annualized placement (+) and removal (-) volumes per cell.*

Cell	Former Placement (+) & Removal (-) Volumes [cy/yr]	Final Placement (+) & Removal (-) Volumes [cy/yr]
N4	1,572	3,269
N3	1,493	3,727
N2	1,493	2,283
N1	1,022	1,522
Inlet Interior	-11,120	-46,806
Inlet Upper	-	-
Inlet Lower	-	-
S1	24,994	12,807
S2	23,808	34,082
S3	21,280	9,646
S4	26,659	21,270

Results

DEP's revision to Dr. Zarillo's sediment budgets is presented for discussion within this section. The budget utilizes the updated annualized placement and removal volumes displayed in Table 6 and was balanced using the SBAS (Sediment Budget Analysis System) toolbox in ArcGIS Pro from the US Army Corps of Engineers to validate the accuracy of the calculations and ensure that no residuals were present in any of the cells.

The revised budget (**Figure 4**) utilizes values for bathymetric change (ΔV) computed using the methodology described on page 6 as the basis for the balancing computations in SBAS. The budget, along with the computation of its target bypassing objective, can be found on page 14. Unlike the unicellular budget presented in Figure 1, this budget does not incorporate offshore transport, as its Q_{Final} of 129,135 cy/yr exiting the system is already less than its $Q_{Initial}$ of 150,000 cy/yr. The sediment budget in Figure 1 expelled 47,939 cy/yr offshore with the intent of reducing its Q_{Final} to better align with the sediment flux entering the coastal littoral system. However, since this is no longer the case, attribution of offshore loss is unnecessary. Moreover, the inlet interior cell (ΔV=-34,173 cy/yr), whose removal volume was revised from -11,120 cy/yr to -46,806 cy/yr (Table 6), now exhibits an accretion of 12,663 cy/yr when dredging activities are eliminated from the cell. This pattern better reflects the anticipated behavior of the flood shoal and sand trap as a sink for sediment attempting to bypass the inlet and is consistent with the fundamentals of inlet sediment transport. Finally, the target bypassing objective for this budget is 82,812 cy/yr, as illustrated in **Equation 3**. This value falls directly between the historical bypassing estimates of 70,000 cy/yr in the 2000 IMP and 90,000 cy/yr in the 2008 SBMP. It is also a substantial increase from the 39,993 cy/yr derived from the unicellular budget in Figure 1.

In summary, this budget resolves each of the outstanding concerns outlined on page 5 and fulfills the objective of DEP's quality assurance analysis. We offered these results to the technical advisory committee on April 5th, 2023 for further discussion in finalizing the sediment budget and target bypassing objective.

Figure 4: *DEP revisions to the Sebastian Inlet sediment budget. ΔV values are presented in white with updated placement (P) and removal (R) values from Table 6. Blue and red cells correspond with areas of accretion and erosion respectively.*

Equation 3:

$$\boldsymbol{T = \sum(\Delta V + |R| - P)_{Updrift;Flood\ Shoal;Ebb\ Shoal;Channel}}$$

$$\boldsymbol{T = [\Delta V + |R| - P]_{N4+N3+N2+N1} + [\Delta V + |R| - P]_{FS} + [\Delta V + |R| - P]_{ES} + [\Delta V + |R| - P]_{In.Up}}$$

$$\boldsymbol{T = [(3,093 + 13,341 + 4,794 + 11,824) - (3,269 + 3,727 + 2,283 + 1,522)]_{N4+N3+N2+N1} + [-34,173 + 46,806]_{FS} + [47,296]_{ES} + [632]_{In.Up}}$$

$$\boldsymbol{T = [22,251]_{N4+N3+N2+N1} + [12,633]_{FS} + [47,296]_{ES} + [632]_{In.Up}}$$

$$\boldsymbol{T = 82,812\ cy/yr}$$

Appendix A: Derivation of the Target Bypassing Objective

Florida Statutes Chapter 161, Section 142 states that it is the intent of the legislature to *"replicate the natural drift of sand which is interrupted or altered by inlets to be replaced and for each level of government to undertake all reasonable efforts to maximize inlet sand bypassing to ensure that beach-quality sand is placed on adjacent eroding beaches."* This intent is fulfilled through an inlet's target bypassing objective, defined as the quantification of the impact of an inlet on the adjacent shorelines.

Conceptually, the target bypassing objective is the sum of the sediment sinks which occur as a direct consequence of the inlet's presence. In other words, an inlet acts as a barrier to longshore littoral drift, causing sand to accrete in specific locations, namely the ebb shoal, inlet interior (flood shoal, inlet channel, etc.), and updrift shorelines (**Figure 5**). Without the inlet's presence, the volume of sand that accretes in these areas would have instead simply shifted to the downdrift shorelines. Therefore, the target bypassing objective identifies the specific quantity of sand which must be transferred to the downdrift beaches to "*replicate the natural drift of sand"* and account for the downdrift deficit of sediment caused by the inlet.

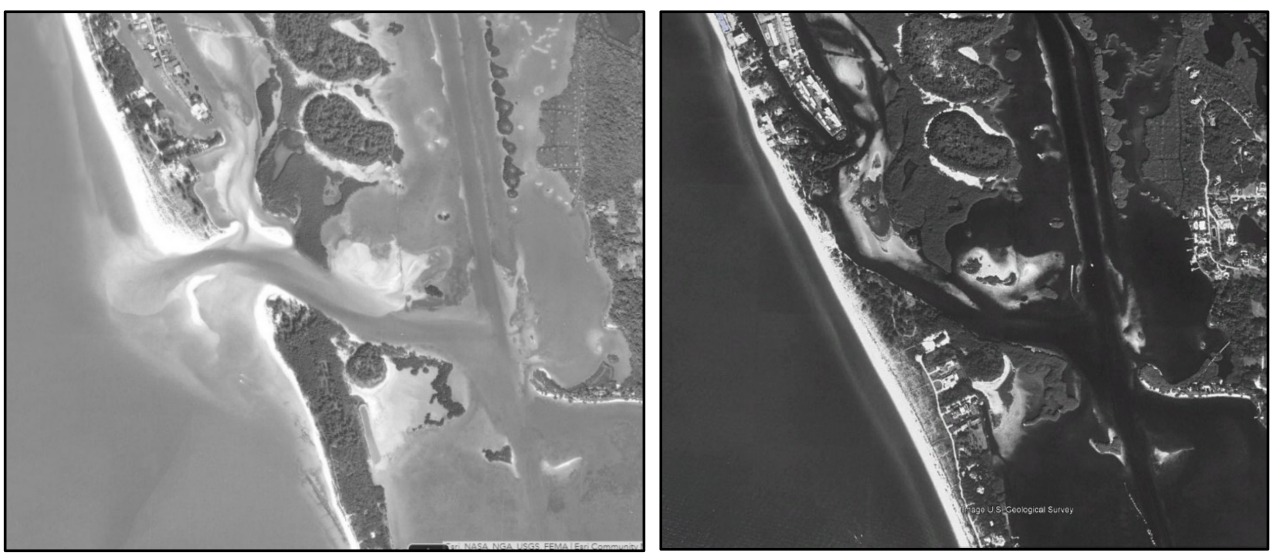

Figure 5: *Aerial imagery of Midnight Pass before (left) and after (right) inlet closure. Note the sinks of sediment coincident with the inlet's presence (ebb shoal, inlet interior, and updrift shorelines). Without the inlet, sediment drifts uninterrupted across the coastal system.*

The target bypassing objective (T) is mathematically defined as the following (**Equation 4**):

Equation 4:

(i) $$\boldsymbol{T} = \sum\left[\begin{matrix}\textbf{Sediment Sinks}\\ \textbf{Directly Caused by}\\ \textbf{The Inlet}\end{matrix}\right] = \sum \Delta \boldsymbol{V}_{\boldsymbol{Sinks}}$$

(ii) $$\boldsymbol{T} = \sum \Delta \boldsymbol{V}_{\boldsymbol{Sinks}} = \Delta \boldsymbol{V}_{\boldsymbol{Updrift}} + \Delta \boldsymbol{V}_{\boldsymbol{Ebb\ Shoal}} + \Delta \boldsymbol{V}_{\boldsymbol{Channel}} + \Delta \boldsymbol{V}_{\boldsymbol{Flood\ Shoal}}$$

In the above equations, ΔV is the annualized volume change in cubic yards per year of a given sediment cell. This formulation provides the basis for calculating the target bypassing objective in the presence of an inlet. However, Equation (ii) does not account for human intervention in the sediment cells of interest, in which thousands of cubic yards of sediment may be annually placed or removed within said cells. Therefore, it is necessary to modify the above equations to eliminate human influence such that we are exclusively identifying the impact of the inlet itself on the adjacent shorelines. Equations (i) and (ii) become (**Equation 5**):

Equation 5:

(iii) $$\boldsymbol{T} = \sum(\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P})_{\boldsymbol{Updrift;Ebb\ Shoal;Channel;Flood\ Shoal}}$$

(iv) $$\boldsymbol{T} = (\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P})_{\boldsymbol{Updrift}} + (\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P})_{\boldsymbol{Ebb\ Shoal}} + (\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P})_{\boldsymbol{Channel}} + (\Delta \boldsymbol{V} + |\boldsymbol{R}| - \boldsymbol{P})_{\boldsymbol{Flood\ Shoal}}$$

In the above equations, R and P are the annualized removal and placement volumes in cubic yards per year of a given sediment cell. The above modification ensures that the target bypassing objective replicates the *"natural drift of sand"* as previously specified in F.S. 161.142. Equation (iv) was applied to the cells of the Sebastian Inlet sediment budgets calculate the target bypassing objective. This mathematical approach has been similarly documented at other inlets across Florida.