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Morphodynamic analysis and numerical modeling of Sebastian Inlet, Florida, USA

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Abstract:
In order to renourish the downdrift beaches at Sebastian Inlet, FL, USA, multiple fill projects have been undertaken over the past 2 decades, with the most recent one in 2007. Sebastian Inlet has undergone intense monitoring by the Sebastian Inlet District (SID) which includes hydrodynamic data (waves, water level, current), hydrographic surveys and aerial images. The data are used to calculate bathymetric and shoreline changes over various time scales, and to apply and calibrate a morphologic model of the Coastal Modeling System (CMS), developed by the US Army Corps of Engineers. Results indicate sand deposition and shoreline advancement south of the project location, and around the ebb shoal system. The model successfully reproduced sedimentation patterns over a year-long run, including a complex cross-shore sand transport along the reef lines. Simulations also demonstrated reversals in the longshore transport direction due to wave refraction around the ebb shoal, providing an explanation which could explain sand back-passing toward the inlet.

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1. Introduction

Florida's coastline has been experiencing increased erosion due to tidal inlet stabilization with jetties for nearly thirty years. In order to renourish the downdrift beaches, numerous fill projects have been undertaken since the 1970's, resulting in various degrees of success. Bathymetric surveys enable the quantification of sand transport. However, overall temporal resolution remains low and prevents the understanding of the short term interactions (within several hours) that occur during storms. Numerical model simulations assist in our understanding of specific sediment transport mechanisms and induced morphologic changes due to certain hydrodynamic conditions. This article presents results from a morphodynamic monitoring and modeling program undertaken for Sebastian Inlet, FL. Bathymetric and shoreline change calculations were performed over a variety of time-scales between 2000 and 2009, including major natural and anthropogenic events (hurricanes and beach fill projects). The morphodynamic data combined with hydrodynamic data were used to set up and calibrate a morphologic model (coupled CMS-Flow/CMS-Wave from USA/CIRP). This model aimed at reproducing sediment transport and morphologic evolution within the inlet system and adjacent beaches.

2. Study area

2.1 Geographic and geomorphologic setting

Sebastian Inlet is located on the East Central Florida coast and separates the Indian River Lagoon from the Atlantic Ocean (figure 1). The barrier island in the vicinity of the inlet rarely exceeds 2 km in width and 10 m height above sea level. The area is characterized by great variety in the sediment size (02 to 0.5 mm) and composition. The inlet reached its present configuration in the 1970's, after the channel was artificially cut into the limestone, a sand trap blasted (western edge of channel), and inlet stabilization implemented by two offset jetties. Local geomorphology is also characterized by reef rock outcrops in the south part of the domain and a large ebb shoal that developed after inlet stabilization and attaches to the downdrift shoreline approximately 1 km south (ZARILLO & BREHIN, 2009).

2.2 Beach fill projects

Beach fill projects cover approximately a 3 km section of the downdrift beach, between R monuments R5 and R16 (figure 1). These benchmarks, which are being used for beach profile monitoring, were placed by the Florida Department of Environmental protection (DEP) at 300 m intervals and (increasing number scheme) from North to South in every county. Beach fill placement totals 1000000 m^3 over the past two decades, and consists of the dredging the interior sand trap or external borrow areas, and subsequent downdrift placement via a system of pumps and pipelines. The largest project over the recent years was the Ambersand project, which dates from 2003 (500000 m^3). The most recent sand trap dredge was performed in 2007 with 80000 m^3 placed on the downdrift beaches. After an intense hurricane season, the project was combined with another project in November 2007 that consisted of 150000 m^3 dredged from an external borrow site. Since 1990, the Sebastian Inlet Tax District (SITD) has performed a morphodynamic monitoring program including bathymetric data and aerial photographs.

2.3 Hydrodynamic climate

A meteorological station on the Sebastian Inlet north jetty and wave gages are maintained by the Florida Tech Coastal Engineering Laboratory (figure 1). The set-up consists of a 1200 KHz RDI Workhouse sentinel (main gage) and a Nortek AquaDopp current profiler (secondary gage) deployed over a 2 to 3 months period. The gages are anchored to the bottom (jet-piped) in 6 m water depth. Both primary and secondary equipment collect wave data at 2 Hz for 1024 samples per burst every three hours. Currents are sampled at 24 Hz for 2 minutes every 30 minutes. The set-up has enabled the characterization of nearshore hydrodynamics over the long term as well as the short term during storm events and hurricanes. These gages are also very useful for calibrating and validating numerical models with waves and currents comparison.

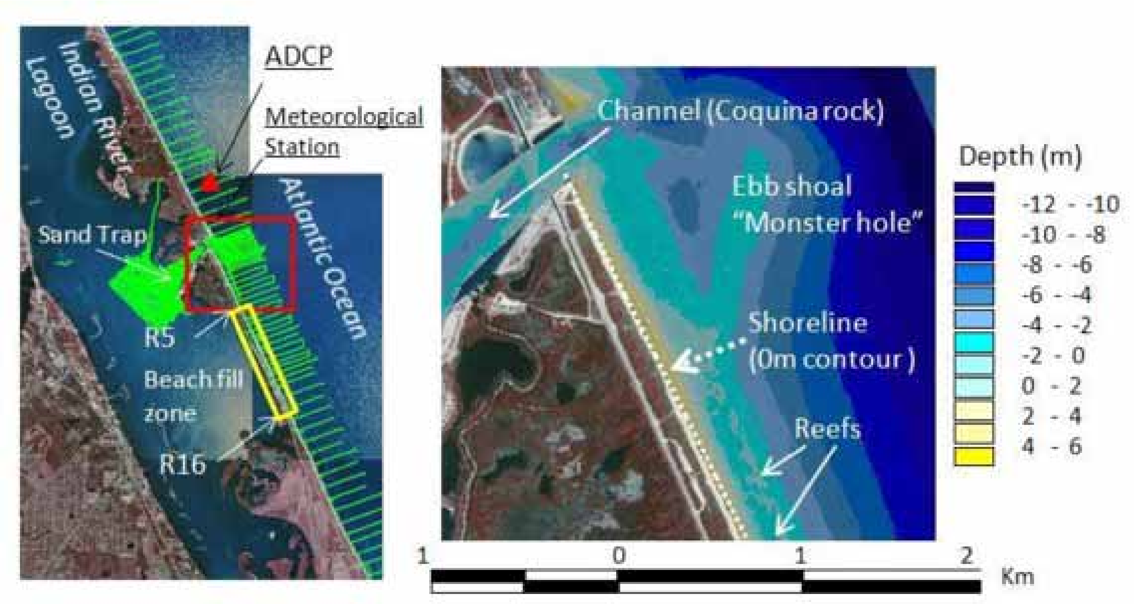


Figure 1. Study area and hydrographic survey data coverage (green dots).

The inlet is wave dominated, with an average annual wave height of 0.6 m (which can reach 3 m during winter nor'easters and summer hurricanes), and a strong seasonal signal. The average littoral drift is directed south and can reach 250000 m^3/yr and is the result of southward transport in winter and northward transport in summer (ZARILLO & BREHIN, 2009). The tide is semi-diurnal microtidal with ocean amplitude near 1 m, and decreases significantly in the back-barrier/lagoon. The combination of a narrow inlet channel and large volume of water in the lagoon (tidal prism of $1x10^7$ m^3) generates strong tidal currents (up to 2.5 m/s between jetties), which prevent sediment deposition and shoaling in the channel and leads to shoal formation. Wave-current interactions create hazardous conditions for navigation within the inlet and prevent field measurements and deployment of equipment.

3. Methods

3.1 Bathymetric and shoreline changes

Hydrographic surveys of the inlet system and surrounding beaches are conducted on a semi-annual basis by the Sebastian Inlet Tax District (SITD) since the winter of 1990. Offshore elevation data are gathered by conventional boat/fathometer surveying methods from -1 to -15 m in accordance with the Engineering Manual for Hydrographic Surveys (USACE, 1990). The coverage includes a 20 km section (figure 1), with maximum spatial resolution in the vicinity of the inlet (varying between 1 to 5 m according to the surveys). Topographic survey data were converted to xyz format and imported into Arcview $3.2^{©}$ Geographic Information System (GIS) software. The horizontal projection was State Plane NAD27 (ft) with vertical datum in NGVD29 (ft), both being converted to metric. All analyses were performed according to the Triangulated Irregular Network surfaces (TIN) method (figure 1), in which surfaces, corresponding to different masks representing the inlet or the surrounding beaches sand reservoirs, are generated for each survey period. Shoreline extraction was performed using those TIN’s (0-hydrographic contour) (figure 1).

3.2 Model description and application

The morphodynamic model is a coupling between wave model (CMS-Wave) and circulation model (CMS-Flow), both part of the Coastal Modeling System (CMS), developed by the US Army Corps of Engineers (USACE) Coastal Inlets Research Program (CIRP). The 2-D depth averaged circulation model (formerly M2D) solves numerically the governing equations for water motion with a finite volume approach and includes a sediment transport routine with possibility to simulate non-erodible/hard bottom cells (BUTTOLPH *et al.*, 2006). The wave model (formerly WABED) is a phase-averaged nearshore wave transformation model which includes refraction, diffraction, reflection, and wave-current interactions (DEMIRBILEK *et al.*, 2007). Models are coupled at 3 hr intervals for the entire year 2007, using the "Steering Module" within the SMS (Surface Water Modeling System) interface. Model grids extend approximately 10 km on both sides of Sebastian Inlet and 5 km offshore (depth of -20 m). The circulation model grid is included inside the wave model grid and cell size ranges from 50 m (nearshore) to 200 m (offshore). The shoreline was digitized using a 2007 aerial image and bathymetry was a combination of the high resolution bottom topography discussed earlier and the lower resolution Coastal Relief Model data (National Geodetic Data Center). Non-erodible (hard bottom) zones within the inlet channel and south side of the domain were obtained from a bottom characterization study by the Florida Institute of Technology Biological Oceanography Laboratory using a Roxanne sonar and included in the model grid. Observation stations were selected within the model grid to extract littoral transport (total of 62 rows of 5 cells over the entire model domain representing nearshore/upper shoreface up to a depth of -3 m). For the sediment transport, the Lund-CIRP formula was used, with average grain size varying between 0.2 and 0.3 mm. For the hydrodynamic model, boundary conditions consisted of water surface elevations extracted from the tidal prediction software package IOS. Time series of water elevations were extracted and applied to the east (ocean), north lagoon and south lagoon boundaries of the model domain. The circulation model inputs also consisted of wind speed and direction from the meteorological station and uniformly applied to the model grid. Boundary conditions for the wave model consisted of wave height, period, and direction (H_s, T_p, D_p) extracted from a larger scale model of CMS-Wave forced with Wavewatch 3 data (TOLMAN, 2009).

4. Results and discussion

4.1 Bathymetric, volumetric and shoreline evolution

Long term bathymetric changes from 2000 to 2009 (figure 2, top left) indicate significant sand deposition on the shoals, sand trap, and beach located directly downdrift of the inlet between the south jetty and attachment bar (up to +2 m). These changes correspond to volumetric gains totalizing near +180000 m^3. The beach section between R1 and R3 undergoes significant shoreline advancement (+35 m) during the same time period (figure 3a), whereas the beach fill zone (R5 to R16) is characterized by overall retreat (-10 to –25 m), and generalized erosion of the beach face and upper shoreface (-200000 m^3). Deposition patches (up to +30000 m^3) were observed on the beaches south of the beach fill zone (R20-R30).

Bathymetric evolution from 2003 to 2007 (figure 2, top right) shows similar trends with the 2000-2009 period: significant erosion (-150000 m^3) of the upper shoreface of the renourished zone (R5-R15), counterbalanced by sand deposition of +50000 m^3 and +75000 m^3 respectively on the beach/upper shoreface directly south of the inlet (R1-R5) and south of the beach fill zone (R15-R30). The above results suggest sediment transport both towards the inlet and the south (interactions with reef outcrops). The shoreline evolution (figure 3b) highlights the advancement south of the beach fill zone

(+25 m), suggesting the 2003 beach fill project has benefited the downdrift zone, rather than the project zone.

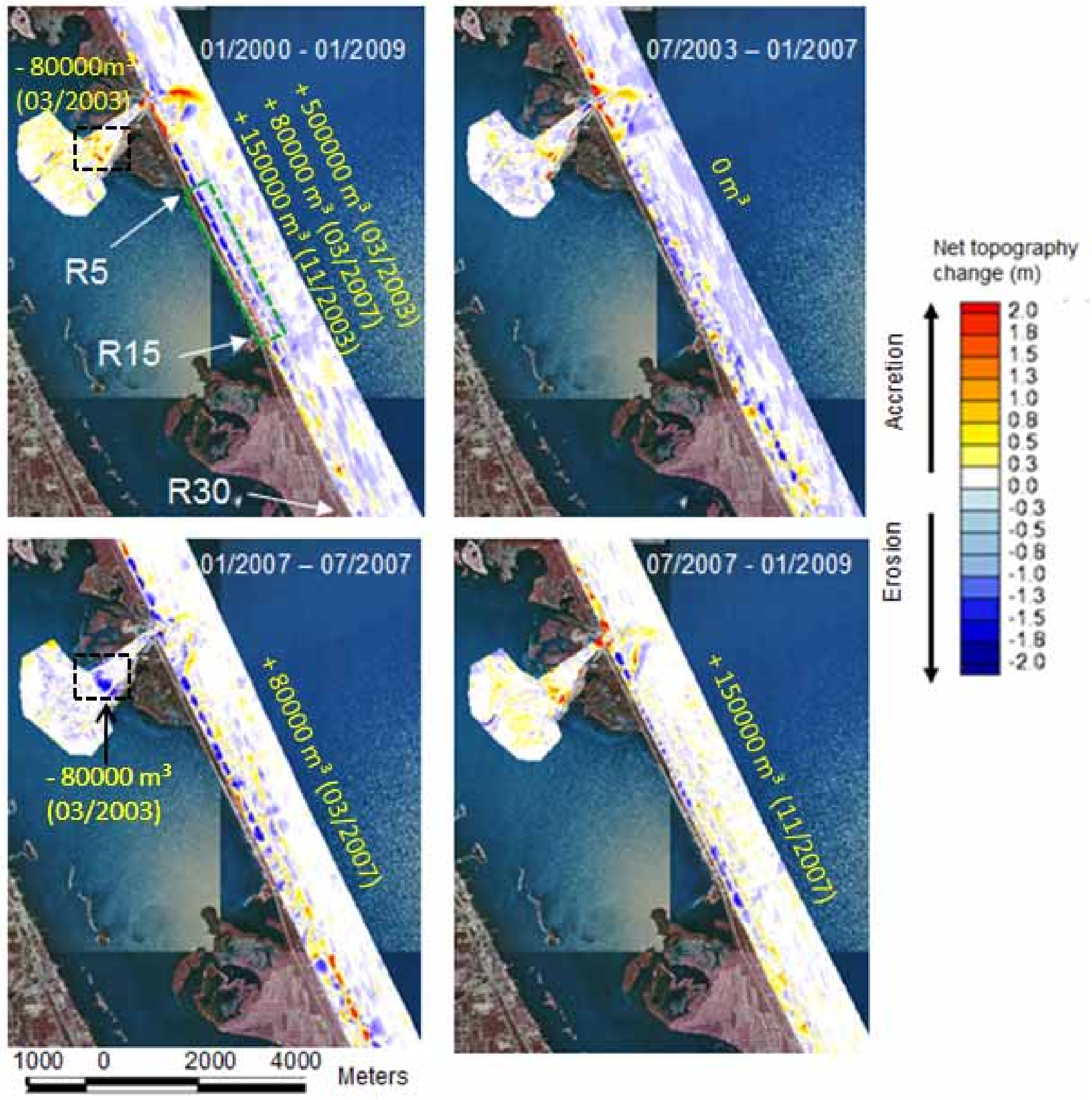
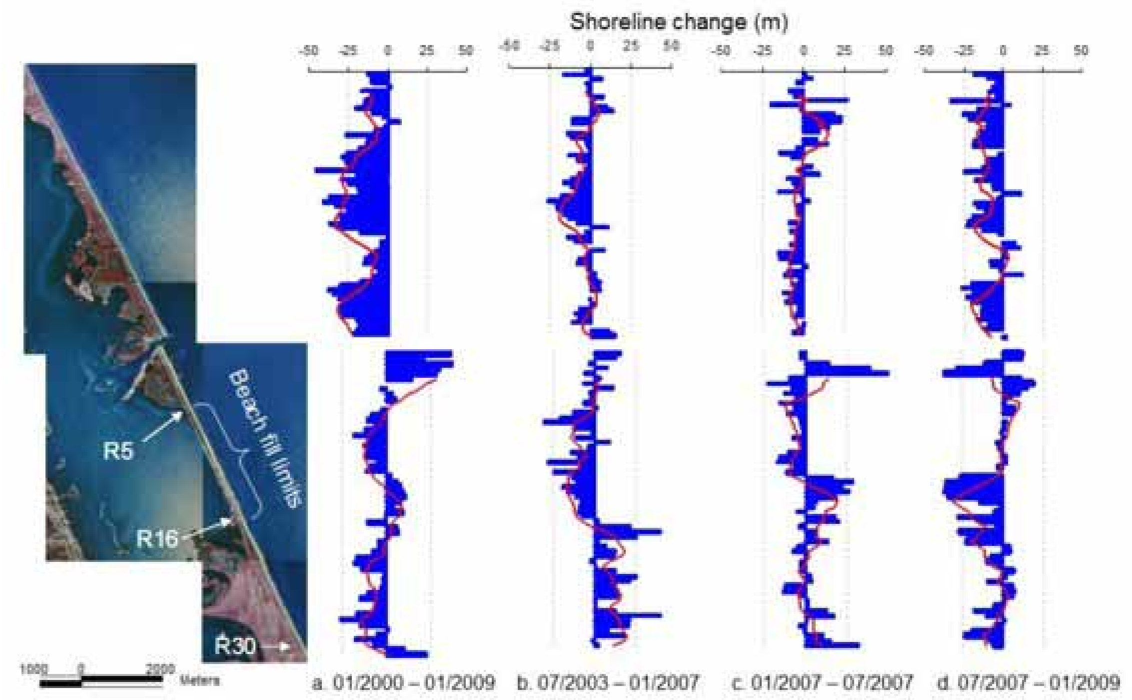


Figure 2. Bathymetric changes for several time periods from 2000 to 2009.

Bathymetric changes from January to July 2007 (figure 2, bottom left) illustrate scouring in the sand trap, resulting from the dredging operations (-80000 m³), and on the upper shoreface of the beach between the south jetty and R15 (-180000 m³). Sand deposition (+30000 m³) was concentrated on the lower shoreface of the beach fill zone (R4-R16), and south of R20 (+80000 m³). These observations, along with the absence of significant deposition on the ebb shoal, suggest a significant southward littoral transport due to Subtropical Storm Andrea (May 2007). The shoreline evolution (figure 3c) indicates the performance of the March 2007 beach fill project, with shoreline advancement concentrated on the beach section between the south jetty and R4 (+50 m) and to the south of R20 (+20 m), whereas the renourished zone undergoes shoreline recession of approximately -10 m. Bathymetric changes from July 2007 to January 2009 (figure 2, bottom right) show similarities with the January to July 2007 period: scouring (-35000 m³) on the upper shoreface of the renourished zone and deposition at the jetty tips and south of the renourished zone (+15000 m³ and +60000 m³, respectively). The shoreline (figure 3d) advances slightly on the renourished zone (+5 to +10 m) and retreats south of R15. This observation is consistent with the deposition observed on the upper shoreface in that zone.



a. 01/2000 – 01/2009 b. 07/2003 – 01/2007 c. 01/2007 – 07/2007 d. 07/2007 – 01/2009

Figure 3. Shoreline changes over several time periods from 2000 to 2009.

4.2 <u>Morphodynamic modeling</u>

The bathymetric evolution predicted by the model over the year 2007 (figure 4, left) indicates significant sand deposition on the ebb shoal (+2 m), upper shoreface and eastern edge of the channel/sand trap (+1 m). Erosion dominates the western side of the channel, lower shoreface, and seaward edge of the ebb shoal. The model enables comparison of morphologic evolution to the hydrodynamic climate. Two important events occurred in 2007. Hurricane Dean, moving accross the Caribbean, generated a medium size long period swell approaching from the SE (H_s=1.2 m, T_p=13 s), representative of the summer low energy conditions. Subtropical storm Andrea moved along the FL coast generating a strong swell from East/North East (H_s=3 m, T_p=15 s), similar to winter storms wave conditions.

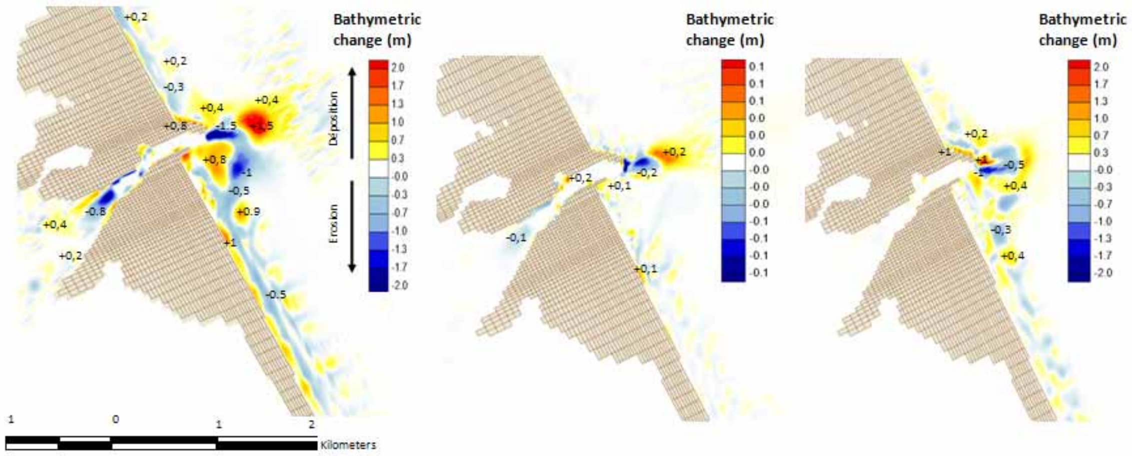


Figure 4. Predicted bathymetric changes: year 2007 (left); Hurricane Dean – 72 hours (middle); Subtropical Storm Andrea – 72 hours (right).

Bathymetric changes predicted by the model for Hurricane Dean (figure 4, middle) show slight erosion (-0.1 m) at the tip of the north jetty, deposition on the seaward side of the ebb shoal (+0.1 m), and minimal changes on the upper shoreface of the adjacent south beaches. Littoral transport (figure 5, middle) is northward and of low intensity (maximum of +250 m^3), which is in agreement with the overall wave conditions.

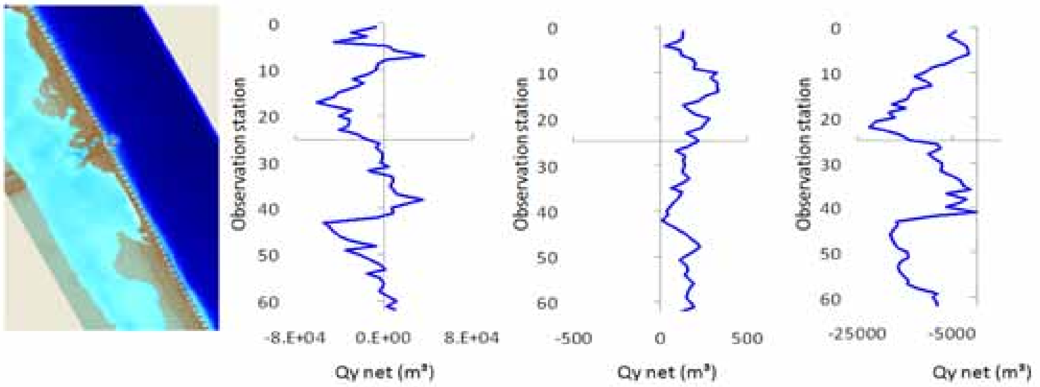


Figure 5. Predicted littoral transport: year 2007 (left); Hurricane Dean – 72 hours (middle); Subtropical Storm Andrea – 72 hours (right).

Changes predicted for Subtropical storm Andrea (figure 4, right) showed greater fluctuations. The model indicates significant sand deposition along the north jetty and on the ebb shoal (+1 m), and oscillation between deposition/erosion on the upper shoreface of the south beach. The southward littoral transport reaches 20000 m^3 over certain zones (figure 5, right). Over the long term (year 2007), the transport is mostly to the south (negative values). Despite the trend in general transport, there exist key exceptions: a reduction in the transport intensity near the inlet and reversal in the direction between the inlet and observation station 50 or R16 (south limit of the beach fill zone). The zone from R16 to R30 is located away from the inlet influence (jetties and ebb shoal system) and therefore south-directed littoral sand transport increases. This zone also experiences variations in the distribution of reef outcrops (figure 6). The reef coverage and cross sections for 3 stations (R5, R15 and R25) indicate that reef outcrops occur farther away from the shore south of R16, and are characterized by a steeper slope. This particular configuration plays a major role in beach fill sand trapping.

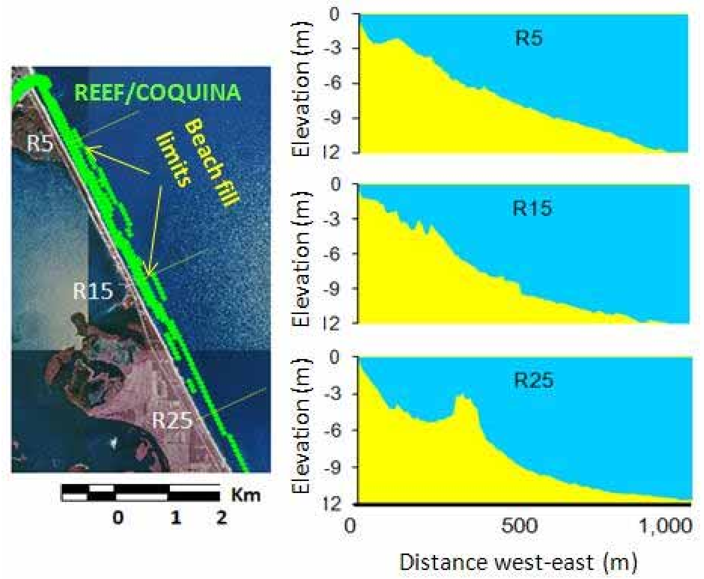


Figure 6. Reef location and cross-sections extracted at 3 stations (R5, R15 and R25) using July 2009 bathymetry.

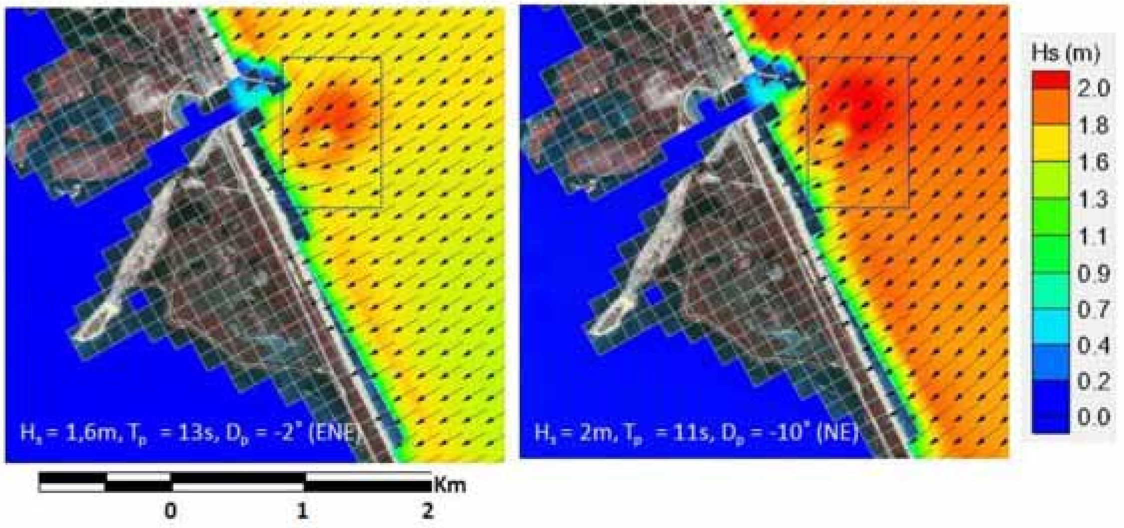


Figure 7. Wave rays calculated by CMS-Wave during Subtropical storm Andrea.

CMS-Wave outputs for typical storm conditions extracted during Subtropical storm Andrea show an increase in significant wave height and a clear refraction pattern around the ebb shoal (figure 7). This refraction pattern may cause a reversal in sand transport direction for the R1-R3 zone under northerly approaching storm waves (figure 8). Simulations further indicate that reversals (and therefore inlet shoaling) are favored during flood stage, while natural sand bypassing is favored during ebb stage.

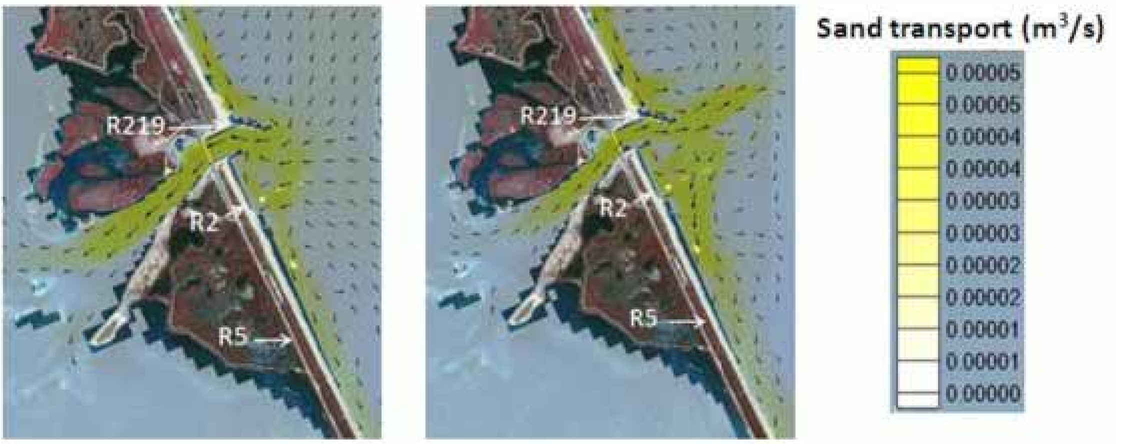


Figure 8. Sediment transport under northerly approaching waves during flood (left) and ebb (right).

5. Conclusions

Bathymetric and shoreline changes in the vicinity of Sebastian Inlet over the past decade showed complex spatial and temporal differences including the distinction between 3 zones on the downdrift/south side of the domain: from the south jetty to R5 (direct inlet influence); from R5 to R15 (beach fill zone); and from R15 to R30 (changing reef distribution). Results highlighted a complex sediment budget and importance of local geomorphology (ebb shoal and reef outcrops) in controlling natural sedimentation and downdrift erosion. The beach fill projects of 2003 and 2007 (total of +730000 m^3 between R5 and R16) contributed to sand deposition on the beaches located behind the ebb shoal, between the south jetty and the attachment bar (R2), and south of the project zone (R15 to R30). From 2000 to 2009, these beaches have experienced volumetric gains (+30000 m^3 and +80000 m^3, respectively) whereas the renourished zone has lost a significant sand volume (-200000 m^3). Morphologic model simulations proved to be successful in predicting the hydrodynamics and sediment transport, as well as the role of the ebb shoal in wave refraction and littoral sand transport reversal between R1 and R3. Future work includes additional model calibration over longer time scales and determination of the CMS model performance using a probabilistic approach (Brier score).

6. References

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