

Process controlling beach nourishment performance at Delray Beach, Florida, USA

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DOI

[10.4233/uuid:aa444a96-7821-4244-ae6e-b2c28c008ef8](https://doi.org/10.4233/uuid:aa444a96-7821-4244-ae6e-b2c28c008ef8)

Publication date

2016

Document Version

Final published version

Citation (APA)

Benedet, L. (2016). *Process controlling beach nourishment performance at Delray Beach, Florida, USA*. [Dissertation (TU Delft), Delft University of Technology]. <https://doi.org/10.4233/uuid:aa444a96-7821-4244-ae6e-b2c28c008ef8>

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Processes Controlling Beach Nourishment Performance at Delray Beach, Florida, USA



Lindino Benedet

Process Controlling Beach Nourishment Performance at Delray Beach, Florida, USA

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen
op dinsdag 5 april 2016 om 12:30 uur

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This thesis should be referred to as: Benedet, L. (2016). *Processes Controlling Beach Nourishment Performance at Delray Beach*. Ph.D. thesis, Delft University of Technology.

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SUMMARY

Beach erosion is a chronic problem in the southeast coast of the State of Florida, where Delray Beach is located. To mitigate increasing erosion problems (subsequent) beach nourishment projects were constructed along the entire sandy coast of the state of Florida. At Delray Beach, the beach was nourished 7 times since 1973 using approximately $5.7 \times 10^6 \text{ m}^3$ of sediments along a stretch of beach of about 4km. Sand for these beach nourishment projects was extracted from an area immediately offshore of the project site, from blanket deposits that overlay bedrock and are located just landward of offshore coral reefs.

Since the construction, Delray Beach has been measured annually by beach profile surveys that extend from the dune to the depth of closure offshore. These monitoring surveys are supplemented by sediment sampling across different water depths and using environmental monitoring investigations. From the analysis of these beach profile surveys it becomes evident that the beach behavior is highly non-uniform alongshore, with persistent areas of extreme erosion, denominated hereinafter erosional hot spots, within the project limits. One particular erosion hot spot located near the south end of the project is responsible for about 50% of the total volume loss from the project limits. Several authors and the city consultant engineer identified these areas of higher erosion and attributed it to different phenomena, such as alongshore variability of sediment grain sizes, offshore gaps in the reef system, or fill end losses due to change in shoreline orientation at the end of the beach fill as it connects with adjacent, non-nourished shorelines. In this thesis all these hypothesis are investigated together with an additional phenomenon, that is, the effect of the offshore dredge pits located immediately offshore of the project site, to seek an understanding of the processes behind the development of persistent erosional hot spots within the geographical boundaries of the Delray Beach nourishment project. This integrated understanding will, in turn, help the beach nourishment design practice and the identification of targeted engineering interventions aimed at reducing the annual volumetric losses of the Delray Beach nourishment program.

Critical evaluation of sediment data for several years was initially conducted to investigate the hypothesis raised by previous authors that higher erosion in the south end of the project is due to the occurrence of finer beach sand at this segment. Data from multiple annual monitoring reports demonstrated that alongshore grain size distribution on Delray Beach varies significantly, temporally and spatially, and that there is no persistent trend of finer grain sizes being located in the erosional hot spot segment compared to the rest of the beach; in fact, grain size differences within the project area can be considered to be minor. This data provided enough evidence to conclude that grain size differences alongshore were not the cause of increased hot spot erosion.

Wave modelling and morphological modelling also suggested that the gaps in the offshore shore parallel reef system were not responsible for hot spot erosion. The effects of the barrier reefs on the nearshore waves and currents were relatively minor as evidenced by numerical model results. Strong alongshore variability in wave height and associated pronounced areas wave shadowing and focusing zones were observed along the project area in initial numerical modelling efforts, but these were attributed to wave transformation over the dredge pits located offshore of the nourished beach. Near the erosion hot spot segment on the south end of the project, however, these variations in nearshore wave heights were relatively small compared to other segments of the project.

Beach changes in the study area are dominated by NE swells that occur in the North Atlantic winter months. During these swell events, alongshore currents are stronger in the erosional hot spot segment in the south end of the project when compared to the rest of the beach. Even though stronger currents were observed at this location, gradients in nearshore wave height were smaller at this location when compared to other project segments so it was not possible during initial analysis to rule out any of the possible remaining hypothesis raised to explain the hot spot erosion phenomena: changes in shoreline orientation in the south end of the beach fill and effect of nearshore dredge pits on incoming waves.

When beach nourishment with dry-beach placement of sediment is constructed on an open beach there are abrupt changes in shoreline orientation at the ends of fill due to the large seaward protuberance introduced by the fill. These changes are smoothed out over time as the fill material is transported alongshore and the fill erodes. If shoreline orientation were the driver of hot spot erosion, it would be expected that hot spot erosion would slow down dramatically, or even cease towards the end of the nourishment design lifetime. At Delray Beach, however, the high erosion rates at the south end of the nourishment project are persistent during the entire beach nourishment lifetime suggesting that other processes, rather than only shoreline orientation, are playing an important role in the erosion of the southern end of the beach fill.

Relative effects of shoreline orientation and dredge pits on the erosional hot spot were further investigated by integrated simulations of waves, flows, sediment transport and beach morphology changes, together with a detailed analysis of forcing in the flow momentum equation using a simplified schematic model that was created inspired in the Delray Beach case. Using the schematic model it is possible to observe that the beach changes behind the deep dredge pits were due to the interaction of wave forces (roller force), differentials in wave setup (pressure gradient term), and variable bed shear stress. Because of the complex interaction between roller force, wave setup gradient and bed shear stress under oblique waves, the zone of current acceleration and hot spot erosion does not necessarily coincide with the area of wave focusing in the study area. In fact it was demonstrated in chapter 4 that in the area of wave focusing on the pressure, gradient forces are opposite to the wave induced roller force, currents and sediment transport accelerate just downdrift of the wave focusing zone, where the erosional hot spot occurs. This explained why in the erosional hot spot segment there are stronger currents and sediment transport potential than anywhere else in the project site, but this area does not coincide geographically with the largest alongshore gradients in wave height.

By applying the lessons learnt from the schematic model to the Delray Beach model and investigating simulations with several different bathymetric configurations (selectively removing dredge pits by interpolation) it was concluded that a dredge pit with a 12 m maximum depth of cut, located in the center of the Delray Beach project area about 1 km offshore, was the main cause for the erosional hot spot (EHS) in the south end of the project, which is located between 1 km and 1.5 km downdrift of the dredge pit. The hot spot is responsible for about 50% of the erosion from the project site. Morphological simulations conducted removing the dredge pit by backfilling resulted in drastic reduction in hot spot erosion but also an increase in erosion in areas previously stable or accretionary because the same dredge pit that is responsible for the EHS is also responsible for beach stability in the middle of the project.

Delray Beach has about 10 dredged pits located directly offshore from the project site, these dredge pits have different shapes and cuts and exert very different levels of influence on incoming

waves and beach changes. Based on this observation Chapter 5 was focused on studying the effects of the different dredge pit design parameters (shape, cross-shore and alongshore length, depth of cut, distance from shore, water depth in which dredging occurs) on incoming waves and adjacent beach volume changes. It was found that nearshore dredge pits can be designed to have minimal impact on adjacent beaches through fine-tuning of dredge pit design parameters, such as cut depth, the cross-shore width of the pit, pit distance from the shore and water depth. A dredge pit that has a long, shore-parallel extent and a narrow, cross-shore extent, with a shallower depth of cut, produces fewer nearshore impacts and it is the most desirable design template. The regional setting (bed slope, water depth, and distance from shore) are also important parameters that influence not only the magnitude but also the location of the dredge pit impacts on adjacent shores and should be considered in design fine-tuning. Because dredge pit effects not only consist of erosion but also beach accretion, manipulation of incoming waves by dredging to create beach accretion in small, localized areas, similar to what is done using artificial submerged reefs can be employed in specific cases.

The last chapter of this thesis focused on two main tasks, one was to reduce the morphology model results sensitivity to the sequencing of wave climate and to make sure that the annual wave climate being used was at the same time computationally efficient and represented well the erosional hot spot at the south end of the project. The second task was to evaluate the effects of engineering interventions such as dredge pit backfilling and coastal structures on hot spot erosion and its impacts to the beach located immediately downdrift of the fill.

Five methods of wave climate schematization designed to reduce a full wave time-series into a representative set of conditions for coastal morphological modeling were evaluated to achieve the first task. Of all the methods of wave climate schematization tested the 'Energy Flux Method' and 'Opti Method' showed best results in terms of representing accurately the sediment transport of the benchmark wave climate with a reduced set of wave conditions. The Energy Flux Method was identified as the preferred technique because it was relatively easy to apply, it is not subjective since waves are selected as a function of wave energy distribution and shows satisfactory performance even when compared to more complex and time intensive methodologies such as the Opti method. The tests conducted in this chapter also indicate that a number of around 12 representative wave cases was enough to represent an annual wave climate compared to a detailed wave climate in our case study. The optimized morphological model, with an annual wave climate consisting of 12 representative wave cases defined utilizing the Energy Flux Method, was applied to evaluate coastal engineering interventions aimed at reducing volume losses from the Delray Beach nourishment project by addressing the hot spot erosion.

Annual morphological model simulations were conducted to evaluate the effects of the placement of groins, detached breakwaters or backfilling offshore dredge pits on the beach nourishment performance in terms of volume losses. A breakwater field or removal of all dredge pits produced the best results with significant reduction in beach volume losses within the project limits with tolerable downdrift impacts. The groin field halted erosion completely within the project site but increased downdrift erosion threefold. Removal of the deep Dredge pit identified as the main cause for the erosional hotspot caused an abrupt modification in the location of erosion hot spots and accretion cold spots within the project limits but had no net effect in volume losses within the beach nourishment limits, confirming the findings reported in earlier chapters of this thesis.

The research conducted in this thesis demonstrates that some engineering solutions such as the backfilling of all the dredge pits or introduction of permeable structures at the downdrift (south) end of the Delray Beach nourishment project can improve the performance of the nourishment reducing volumetric losses with mild downdrift effects. Since the downdrift beaches are receiving sediment lost from the nourishment project “free of costs”, a 50 per cent reduction of these losses implies that the downdrift beaches will still be receiving sediments, but half the amount. Each intervention will, however, impact updrift and downdrift beaches in a different way; have its costs and its environmental impacts, therefore, before further consideration for implementation of these significant project modifications a complete engineering, economic and environmental feasibility analysis is recommended.

SAMENVATTING

Strand erosie is een chronisch probleem aan de zuidoostkust van de staat Florida, waar Delray Beach gelegen is. Om toename van erosie problemen te beperken, werden langs de gehele zandkust van Florida suppletie projecten aangelegd. In Delray Beach heeft sinds 1973 keer suppletie plaats gevonden, met een totaal van ongeveer 5,7 M m³ sediment langs een stuk strand van ongeveer 4 km. Zand voor deze suppletie projecten werd uit het gebied gehaald dat onmiddellijk offshore van het project ligt, uit zandafzettingen op rotsen, vlakbij de dichtbij gelegen koraalriffen.

Sinds de aanleg van Delray Beach, heeft een jaarlijks strandprofielonderzoek plaats gevonden van het duin tot net landwaarts van de zandbanken voor de kust. Deze onderzoeken worden aangevuld met sedimentmonsters op verschillende waterdieptes langs de kust en met milieu controles. Uit de analyse van deze strandprofielenquêtes wordt duidelijk dat de kust binnen de grenzen van het project zich niet uniform gedraagt en gekenmerkt wordt door gebieden van extreme erosie, de zogenaamde “erosie hotspots.” Een specifieke erosie hotspot, gelegen in het meest zuidelijke gebied van het project, is verantwoordelijk voor ongeveer 50% van het totale verlies binnen het territorium van het project. Verschillende auteurs en de stadsconsulent hebben deze gebieden van hogere erosie geïdentificeerd en schrijven de erosie toe aan fenomenen, zoals variabiliteit en grootte van sediment langs de kust, lacunes in het rif systeem, of verlies van volume te wijten aan de veranderingen in de kustlijn oriëntatie, daar waar deze grenst aan een kust waar geen suppletie heeft plaats gevonden. In dit proefschrift worden al deze hypothesen onderzocht, samen met toegevoegde verschijnselen, zoals het effect van de offshore baggerkuilen in de nabijheid van het project, om de ontwikkelingsprocessen van permanent eroderende ‘hotspots’ binnen de geografische grenzen van het Delray Beach suppletie project beter te begrijpen. Dit zal bijdragen aan een beter inzicht in strand suppletie ontwerpen en aan de identificatie van technische interventies, gericht op vermindering van jaarlijkse verlies van volume van de Delray Beach suppletie, en, welke dan elders kan worden toegepast.

In eerste instantie werd gedurende enkele jaren een kritische beoordeling van sediment gegevens uitgevoerd om de hypothese te onderzoeken dat de hogere erosie in het zuidelijke gebied van het project te wijten zou zijn aan het fijnere zand van het strand. Gegevens uit meerdere jaarlijkse voortgangsverslagen hebben aangetoond dat de korrel-grootte-distributie van Delray Beach aanzienlijk varieert, zowel in tijd als in de ruimte, en dat er geen tendens is dat fijnere korrels zich in dit deel van de ‘hotspot’ bevinden in vergelijking met de rest van het strand; in feite, verschillen in grootte zijn minimaal. Deze gegevens bewijzen en leiden tot de conclusie dat de verschillende groottes niet de oorzaak van de ‘hotspot’ erosie zijn.

Door modellering van golven en morfologie kan vastgesteld worden dat de lacunes in het rif langs de kust niet verantwoordelijk zijn voor toename van ‘hotspot’ erosie. De gevolgen van de barrière riffen voor de kustlangse golven en stromingen waren volgens de numerieke modelresultaten relatief klein. Sterke kustlangse variabiliteit in golfhoogte en in specifieke gebieden van golf-schaduw en concentratie zones werd waargenomen in de eerste numeriek modelleringen in het projectgebied, maar deze werden toegeschreven aan golf-transformaties over de baggerkuilen gelegen in de nabijheid van het suppletie strand. In de buurt van het ‘hotspot’ erosie segment in het zuiden van het project, waren deze variaties in golfhoogte echter relatief klein in vergelijking met andere segmenten van het project.

Veranderingen in het strand van het studiegebied worden gedomineerd door noordoostelijke deiningen, die tijdens de wintermaanden in de Noord Atlantische Oceaan voorkomen. Tijdens deze deiningen zijn stromingen sterker in het segment van de 'hotspot' in het zuidelijke deel van het project, dan vergeleken met de rest van het strand. Hoewel sterkere stromingen werden waargenomen op deze locatie, is het verloop in golfhoogte kleiner op deze locatie in vergelijking met andere project-locaties, en hierdoor was het niet mogelijk om tijdens de eerste analyse een van de mogelijke resterende hypothesen van de 'hotspot' erosie te sluiten: veranderingen in de stand van de kustlijn in het zuiden van de suppletie van het strand en het effect van het baggeren voor de kust op de inkomende golven. Wanneer de suppletie van een strand op droog-zand sediment, en op een open strand, wordt gebouwd, vinden er als gevolg van de in zee uitstekende landtong abrupte veranderingen aan de uiteinden van de kustlijn plaats, geïntroduceerd door de suppletie. Deze veranderingen worden na verloop van tijd, naarmate kustlangtransport plaatsvindt en de kust erodeert, genormaliseerd. Als de kustlijn oriëntatie de drijfveer van 'hotspot' erosie is, zou men verwachten dat 'hotspot' erosie dramatisch zou vertragen, of zelfs, aan het einde van de levensduur van het suppletie-ontwerp zou stoppen. In Delray Beach echter, blijft hoge erosie in de zuidelijke locatie van het project tijdens de gehele periode optreden, waardoor de suggestie wordt gewekt dat er andere processen werkzaam zijn.

Relatieve effecten van de kustlijnoriëntatie en de bagger kuilen op de erosie 'hotspot' werden verder onderzocht door geïntegreerde simulaties van golven, stromen, sediment transport en morfologische veranderingen van het strand, samen met een gedetailleerde analyse van geforceerde stroommomentum dynamiek vergelijking, met behulp van een vereenvoudigd schematisch model, geïnspireerd door Delray Beach. Met behulp van het schematische model is het mogelijk om te constateren dat de veranderingen van het strand achter de diepe bagger kuilen gerelateerd zijn aan de interactie van golfkracht (roller-kracht), verschillen in golf setup (waterspiegel-druk), en variabele bodemschuifspanning. Vanwege de complexe interactie tussen roller-kracht, golf-setup verloop en bodemschuifspanning, onder schuine golven, vallen de zone van stroomversnelling en van de 'hotspot' erosie niet noodzakelijkerwijs samen met de golfstudies in het onderzoeksgebied. In feite, wordt in hoofdstuk 4 aangetoond dat de hellings-druk krachten in het golfgebied tegengesteld zijn aan de door de golf veroorzaakte rol-kracht; stromingen en sedimenttransport versnellen alleen stroomafwaarts van de golf gericht zone, waar de erosie 'hotspot' zich bevindt. Dit verklaart waarom er in het segment van de erosie 'hotspot' een sterkere stroming- en sedimenttransport potentieel bestaat dan ergens anders in de projectsite, maar dit gebied valt niet geografisch samen met het grootste kustlangs verloop in golfhoogte.

Door de toepassing van de lessen uit het schematische model om het model Delray Beach en onderzoek van de simulaties met verscheidene verschillende bathymetrische configuraties (selectief verwijderen van baggerkuilen door interpolatie), kan geconcludeerd worden dat een bagger kuil met een maximale diepte van 12 m, in het centrum van het projectgebied van Delray Beach en ongeveer 1 km van de kust af gelegen, de belangrijkste oorzaak voor de EHS in het zuidelijk gebied van het project was, gelegen tussen 1 en 1,5 km stroomafwaarts van de baggerkuil. De 'hotspot' is verantwoordelijk voor ongeveer 50% van de erosie van de projectsite. Morfologische simulaties met de verwijdering van de baggerkuil door deze opnieuw te vullen, resulteerde in een drastische vermindering van 'hotspot' erosie, maar ook in een toename van erosie in gebieden die daarvoor stabiel waren of aanwas plaats vond omdat dezelfde baggerkuil verantwoordelijk voor EHS ook verantwoordelijk is voor de stabiliteit van het strand in het midden van het project.

Delray Beach heeft een groot aantal baggerkuilen, niet ver uit de kust van het projectgebied. Deze baggerkuilen met verschillende vormen hebben ieder een zeer verschillende invloed op de inkomende golven en het strand. Op basis van deze constatering is hoofdstuk 5 gericht op het bestuderen van de effecten van de verschillende baggerkuil-ontwerpparameters (vorm, kruislings- en kust-langszijde lengte, diepte van de kuil, afstand van de oever, waterdiepte waarop gebaggerd wordt) op inkomende golven en volumeveranderingen van het aangrenzende strand. Baggerkuilen die niet ver uit de kust liggen kunnen ontworpen worden met een minimaal impact op aangrenzende stranden door fijne afstemming van de ontwerpparameters van baggerkuilen, zoals diepte, breedte van de kruislingse ligging van de kuil en, als de zand reserve groot genoeg is, door de afstand van de kust en de waterdiepte. Een baggerkuil, lange en parallel aan de kust en een smalle kruislings op de kust gelegen deel, niet diep, heeft minder effect op de kust en is het meest wenselijke ontwerp. De ligging van het land (bed helling, waterdiepte en afstand van de oever) is ook een belangrijke parameter, die invloed heeft op, niet alleen de omvang, maar ook de locatie van de baggerkuil met gevolgen voor aangrenzende kusten, en moet in acht worden genomen in de verfijning van het ontwerp. Baggerkuilen zijn niet alleen oorzaak van erosie maar hebben ook effect op accretie van het strand; manipulatie van inkomende golven met behulp van baggerwerk leidt tot strand-accretie in kleine, gelokaliseerde gebieden, vergelijkbaar met wat er gebeurt met behulp van kunstmatige verzonken riffen, kan in specifieke gevallen gebruikt worden.

Het laatste hoofdstuk van dit proefschrift is gericht op twee hoofdtaken: (1) is om de gevoeligheid van de morfologische modelresultaten te verminderen op golfklimaat, en, om er verzekerd van te zijn dat de jaarlijkse golfklimaat data op de dezelfde tijd met een maximale computer gestuurde efficiëntie en goede representatie van de erosie “hotspot” in het zuidelijke gebied worden gebruikt; (2) de effecten van technische interventies te evalueren, zoals navulling van baggerkuilen en kuststructuren, op de erosie ‘hotspots’ en de effecten op het nabij stroomafwaarts gelegen strand.

Vijf benaderingen van een geschematiseerd golfklimaat ontwerp om een gehele golfserie tot een set van representatieve voorwaarden voor een morfologische kustmodel te reduceren en weer te geven, werden geëvalueerd in het kader van de eerste taak.

Van alle geteste geschematiseerde methoden van golfklimaat, toonden de ‘Energy Flux Method’ en de ‘Opti Method’ de beste resultaten, in termen van een nauwkeurige representatie van sedimenttransport van het geijkte golfklimaat met een beperkte reeks van golfvoorwaarden.

De ‘Energie Flux Method’ werd geïdentificeerd als de geprefereerde techniek omdat deze relatief eenvoudig is toe te passen, deze niet subjectief is, golven zijn geselecteerd als een functie van golfenergie distributie en, zelfs in vergelijking met de meer complexe en tijdsintensieve methoden, zoals de ‘Opti-Method,’ bevredigende prestaties tonen. Uit de testen, uitgevoerd in dit hoofdstuk, blijkt dat ongeveer 12 representatieve golf studies voldoende waren om een jaarlijks golfklimaat, in vergelijking met een gedetailleerd golfklimaat, in onze casestudy te vertegenwoordigen. Het geoptimaliseerde morfologische model werd met een jaarlijkse golfklimaat, bestaande uit 12 representatieve golfstudies gedefinieerd met behulp van de ‘Energy Flux Method,’ toegepast om de technische kust interventies gericht op vermindering van volumeverlies uit het Delray Beach suppletie project, en met name de ‘hotspot’ erosie aan te pakken.

Jaarlijkse morfologische modelsimulaties werden uitgevoerd om de effecten van de plaatsing van strandhoofden, vrijstaande golfbrekers of navullen van bij de kust gelegen baggerkuilen op het strand suppletie in termen van volume verlies te evalueren. Een golfbrekerveld of de verwijdering van alle baggerkuilen had de beste resultaten, met een significante vermindering van strand volumeverlies binnen de grenzen van het project, met maximaal toelaatbaar stroomafwaarts effect. Het veld van stopgezette erosie volledig binnen de projectsite, maar stroomafwaartse erosie is verdrievoudigd. Verwijdering van de diepe baggerkuil, geïdentificeerd als de belangrijkste oorzaak voor de geërodeerd 'hotspot,' een abrupte wijziging in de locatie van de 'hotspots' van erosie en accretie koude plekken binnen het project veroorzaakt beperkt, maar had geen netto effect in volume verlies binnen de grenzen van het suppletie gebied, bevestigen de bevindingen gerapporteerd in eerdere hoofdstukken van deze thesis.

In dit proefschrift wordt aangetoond dat onderzoek naar technische oplossingen, zoals het opvullen van alle baggerkuilen of het invoeren van doorlaatbare structuren stroomafwaarts (ten zuiden) van het Delray Beach suppletie project, de suppletie kan verbeteren, door het vermindering van volume verlies met milde stroomafwaartse effecten. Sinds de stroomafwaartse stranden "gratis" sedimentaanwas krijgen vanuit het suppletie project, impliceert een vermindering van dit half verlies, dat de stroomafwaartse stranden nog steeds, maar slechts de helft aan sediment zullen ontvangen. Elke interventie zal op de een of andere wijze, zowel op de stroomop- als stroomafwaartse stranden van invloed zijn, koste en invloed op het milieu hebben. Dientengevolge, voordat de uitvoering van dergelijke belangrijke project wijzigingen wordt geïmplementeerd, zal derhalve een volledige technische, economische en ecologische haalbaarheidsanalyse worden aanbevolen.

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CHAPTER 1. INTRODUCTION

Beaches and other coastal features such as inlets and deltas are some of the most dynamic environments on earth, these complex environments experience constant change due to the action of waves, currents, tides and sediment supply (Carter, 1988). Nearshore, surf zone and beach morphology molded by wave and current action manifests in the form of unique spatio-temporal shapes and arrangements (i.e. Wright and Short, 1984). Human interventions that attempt to stabilize such dynamic environment tend to have adverse effects on beach stability and cause sediment imbalances leading to beach erosion. These effects are exacerbated by sea level rise and, in some areas, land subsidence. Beach erosion is a chronic problem in the area studied in this thesis and a subject of great public concern around the world. According to Esteves and Finkl (1998) about 194.8 (15.7%) of the 1,242 km of Florida beaches are eroding, of which 123.7 km (10%) are critically eroded shorelines (CEA).

Beach nourishment is nowadays the preferred method of coastal restoration. Beach nourishment is employed preferentially as a mitigation procedure on eroded coasts around the world (Finkl and Walker, 2002), consequently, large volumes of sand are used to restore eroded beaches. In the United States, for example, project sediment volumes between 1 million m³ and 2 million m³ are common, with some single nourishments approaching volumes on the order of ten million m³ or more (e.g. Miami Beach and Panama City Beach) (Finkl, Benedet, and Campbell, 2006). In other sandy coasts around the world the situation it is not different; along the Dutch Coast, for example, there is a country-wide beach nourishment program that uses increasing volumes of sand to maintain its beaches and dunes, the country's first line of defense. The Dutch annual beach nourishment volume has increased from 6 million m³/yr in 1990 (Hanson *et. al.*, 2002) to 12 million m³/yr in 2012 (Stive *et. al.*, 2013). Large volumes of sand are also used in other engineering applications, such as the construction of ports and breakwaters. Because large sediment volumes cannot be efficiently and economically trucked to the beach, sand deposits on the inner shelf are a common sediment source.

Dredging of nearshore sand deposits, however, introduces large anomalies in nearshore bathymetry that, in turn, may influence wave transformation, nearshore currents, and sediment transport patterns as observed in the study area and reported in subsequent chapters of this thesis. Gradients of sediment transport induced by nearshore dredge pits effect patterns of beach change, causing zonation in beach erosion patterns, development of erosional hot spots, and sediment deposition that results in zones of beach accretion (e.g. Bender and Dean, 2003; Benedet, Finkl and Hartog, 2007).

In order to properly manage nourished beaches, it is important to understand the interactions of the beaches with offshore dredging features, the nourishment interaction with neighboring submerged and emerged morphological compartments, the alongshore variability in beach nourishment response that causes the developments of areas of extreme erosion (erosional hot spots) and stable segments (cold spots) etc. Ultimately, one must understand how the beach nourishment evolves over time in order to properly plan and optimize future nourishment maintenance events. In this thesis the author attempts to contribute to this understanding by studying a well-documented beach nourishment program located in the SE coast of the state of Florida, USA – Delray Beach.

1.1. BEACH NOURISHMENT PROGRAMS IN THE USA

The U.S. coastal protection strategies evolved during the 20th century from coastal structure (groins and seawalls) to beach nourishments. Earlier nourishments were generally fills of opportunity from navigation dredging. In the 1970's major nourishments were constructed to address erosion, storm protection and recreation, and the trend continues to this day. Beach nourishment programs are a series of constructions that periodically place beach-compatible sand in the nearshore to compensate for a net deficit of sand in a given beach system. Beach nourishment is advantageous over other methods of coastal protection (*e.g.* coastal structures) because it preserves the aesthetic and recreational values of protected beaches by replicating the protective characteristics of natural beach and dune systems and dunes. It also generally benefits rather than impacts adjacent beaches (Finkl and Walker, 2003; Campbell *et al.*, 2003).

Several nourishment types and approaches are practiced around the world. Nourishments can generally be distinguished by location and methods of fill placement, design strategies, and techniques, and what's is commonly referred in the USA 'fill densities', that is, m^3/m of fill (NRC 1995; Hanson *et al.* 2002; Dean, 2002). Types of nourishment according to placement of the fill include dune nourishment; nourishment of subaerial beach (berm); profile nourishment (subaerial and submerged); and bar or shore face nourishment (submerged fill). The Dutch have been intensively practicing shore face nourishment over the past decade and innovated once again recently constructing gigantic cross-shore fills to serve as a feeder beach to adjacent shoreline, as exemplified by the sand engine pilot project (Stive *et al.*, 2013).

In the study area, Delray Beach, and across the USA most beach nourishments consist of subaerial nourishments. Beach nourishment projects generally have two components, a design (targeted) beach template, and advanced fill needed to maintain the design beach during the design lifetime. Both components are placed at the same time in a construction template that is usually steeper than the natural beach, and it is generally expected that the construction template 'equilibrates' to the design beach shape in 3-6 months. A schematic illustration of depiction of these components is shown in Figure 1.1. The same components illustrated in plan-view, using the Delray Beach 2002 renourishment project during construction as an example is shown in Figure 1.2.

Of these components, the design beach is generally determined by an iterative process that evaluates costs and benefits as a function of width and goals of the nourishment. Advanced fill is often designed to minimize annual costs of the periodic nourishment, the design engineer needs to calculate the adequate volume of advanced fill to maintain the design beach intact during the design lifetime (NRC, 1995, Dean, 2002, Campbell and Benedet, 2004). If the beach perform as planned by design, subsequent renourishment projects (maintenance) will only replace the advanced fill component and not rebuild the design beach. Typical phases of a comprehensive nourishment program include but are not limited to: (1) Establishment of baselines and objectives; (2) Determination of costs, benefits and impacts from implementing a project at a feasibility level; (3) Investigation of sand sources for the project; (4) Analysis of coastal process and forces at the site to form the basis for design and estimates of project performance; (5) Project design including the quantification of design fill, advanced fill, definition of the construction template and estimates of project performance and design lifetime; (6) Project permitting; (7) Construction initial nourishment project; (8) Post-construction physical monitoring to evaluate project performance;

(9) Validation of design assumptions with post-construction data; (10) Identification of design strengths and deficiencies; (11) Development of design refinements based on lessons learned from monitoring data; (12) Development and maintenance of a public awareness program; (13) Decide when re-nourish the beach based on post-construction monitoring data (14) Renourishment project (NRC, 1995, Campbell et al., 2003).

There are two distinct approaches to beach nourishment design on the U.S., (1) the Federal design process developed by the USACE and (2) non-federal design process developed by private companies that are constructed by local governments and private owners. The essential difference between these two approaches is that Federal projects have standardized design that follows the guidelines of the Coastal Engineering Manual (USACE, 2002). While locally constructed projects follow somewhat similar design approaches they can be more flexible and utilize adaptive management to its full extent.

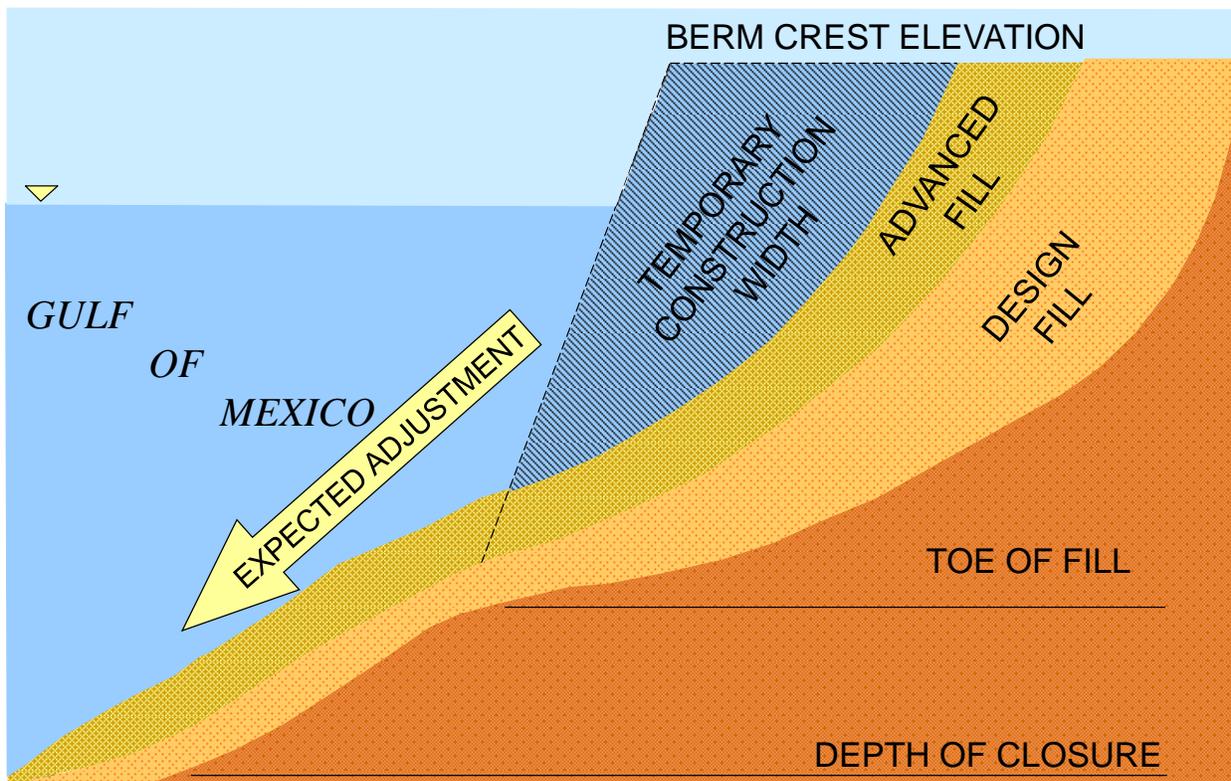


Figure 1.1. Typical components of a subaerial beach nourishment in the US.

The performance of the nourished beach is mostly affected by the textural properties of the sand used to nourish the beach and wave regime. Procedures to evaluate compatibility between native and borrow sands date back to the works of Krumbein and James (1965; James 1975 and SPM 1984). These methods evaluate sand textural differences by the use of empirical parameters: the overfill factor (RA) and the renourishment factor (RJ) (SPM, 1984). The overfill parameter (RA) addresses differences in grain size and sorting between borrow and native beach sediments. The overfill parameter predicts the volume of borrow material necessary to produce an identical unit of fill material (the same grain size as the native beach sand). The renourishment parameter

(RJ) is an empirical parameter that relates to the finer borrow material's greater susceptibility to suspension and transport to estimate renourishment needs.

Recent work conducted by Dean (1991, 2002) suggest a performance based analysis in lieu of RA and RJ to estimate beach fill volumetric requirements and performance. Present design approaches to beach nourishment in the USA favor the use of equilibrium profile considerations, (Dean's method to determine compatibility of borrow source and beach sediments), beach fill performance analysis through monitoring data and use of adaptive management to refine the original design as lessons are learnt from the monitoring data. Fill performance analysis methods include critical evaluation of monitoring data (when available), analytical methods, numerical modeling, or a combination of these methods.

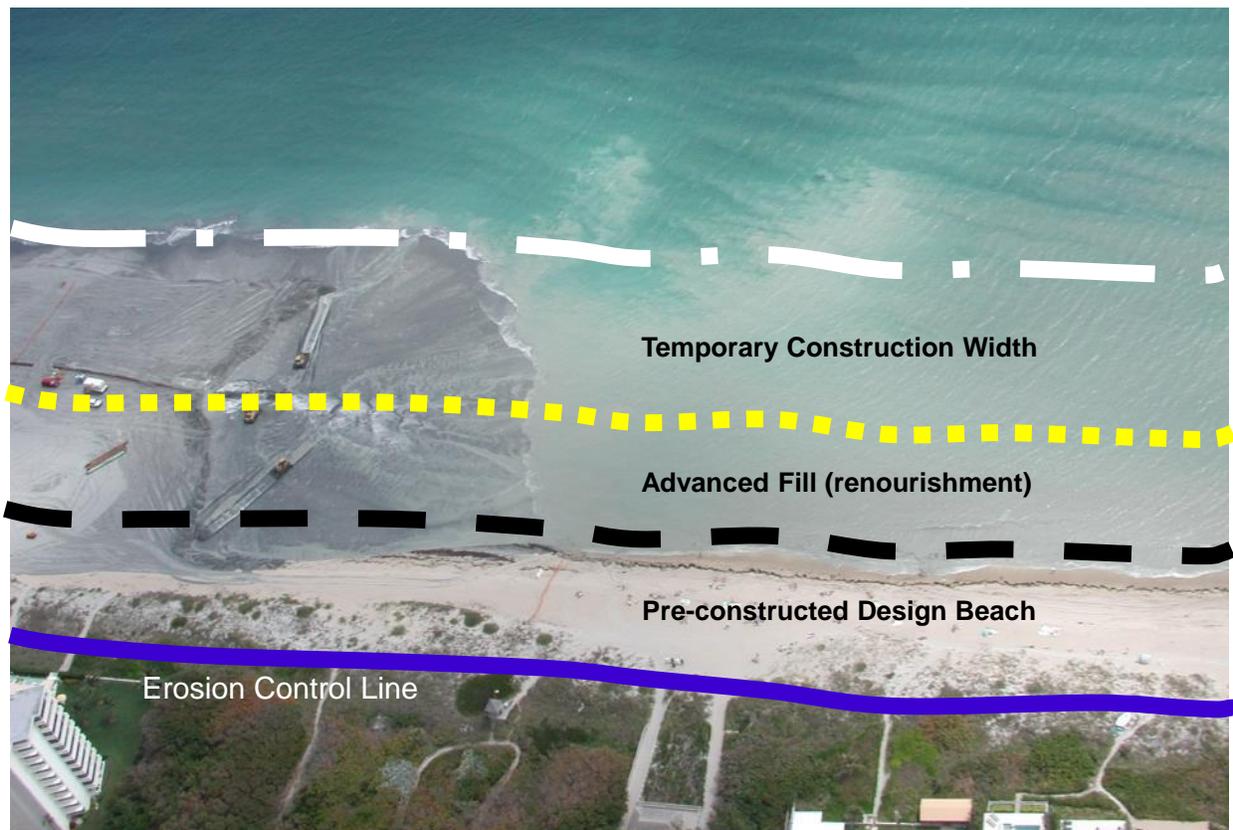


Figure 1.2. Illustration of the main beach nourishment components for the Delray Beach renourishment project constructed in 2002.

The Dean Equilibrium profile method (see Dean, 1991, 2002) suggest that sand of a specific grain size will take a certain shape at equilibrium that is concave upward as the profile transitions offshore from the shoreline to the sand depth of closure. The finer the grain size, the flatter the offshore profile. Analysis of the initial performance of a fill project can thus be based on the process of returning the system to equilibrium. For beach nourishment design, it is important to accurately estimate the dry beach width that results after initial profile equilibration. For example, when compared to native beaches, finer sands will produce milder slopes and generate non-intersecting profiles resulting in narrower dry beach per m^3 of sand placed on the beach. Conversely, coarser sands will exhibit steeper slopes (intersecting profiles) and produce greater

subaerial beach volumes per m³ of sand placed on the beach. Similar sands will tend to replicate the natural beach profile in terms of profile shape (Dean, 2002).

There are two dominant processes to the design and performance of most beach nourishment projects: cross-shore profile equilibration, and lateral spreading of fill material to adjacent beaches (NRC 1995; Dean 2002). Both processes occur simultaneously immediately after fill placement. Other processes that may account for losses of sediment from the active beach system include: relative sea level rise and background erosion, loss of sediments to expanding tidal inlets (Fitzgerald *et al.* 2003), overwash processes on barrier islands (Campbell and Benedet, 2003) and planform adjustments of headland bay beaches.

Numerical models may be used to predict cross-shore responses of nourished profiles to storms and alongshore transport of fill sediments. Fill lateral spreading can also be initially estimated by empirical methods that associate fill length and grain size to fill spreading rates (*e.g.* Dean, 2002, Dean and Yo, 1992). Recent advances in numerical modeling of beach morphology (*i.e.* Roelvink and Reniers, 2014) have enabled the simulation of fill lateral spreading in combination with other processes that induce background erosion prior to fill placement, effects of nearshore bathymetry on fill performance, inlet effects, sea level rise etc.

In a well-managed nourishment program, renourishment designs should consider post-nourishment monitoring data to refine the beach volume needs and calibrate initial analytical and numerical model predictions. Monitoring is important because the performance of a sand starved beach (pre-nourishment), which is commonly used for model calibration, will likely differ significantly from the sand-rich beach system post-nourishment. The nourishment construction may also include disturbances in the nearshore bathymetry through dredging, changes in shoreline orientation or changes in beach grain size that will significantly affect post-construction beach behavior. When long-term (*e.g.* more than 10 years) monitoring data is available for a nourishment program the prediction of future nourishment needs can benefit from the analysis of the measured erosion rates of the nourished beach. If persistent erosion anomalies are observed in the measured data, like erosion hot spots, studies can be conducted to find engineering strategies to properly handle the erosion hot spots and reduce overall erosion rates of the nourished beach.

1.2. THE DELRAY BEACH NOURISHMENT PROGRAM

Delray Beach, the study area, is located in southern part of Palm Beach County about 80 km north of Miami Beach on the Florida southeast coast. Nearby inlets include south Lake Worth Inlet 10 km to the north and Boca Raton inlet 13 km to the south (Figure 1.3). The beach is marked by beach profile monuments put in place by the Florida Department of Environmental protection (FDEP). These beach profile monuments, or R monuments, are utilized in annual beach monitoring surveys. The original Delray Beach nourishment project, constructed in 1973, extended from R175 to R188, while the most recent nourishments (2002, 2013) extended from R179 to R188.

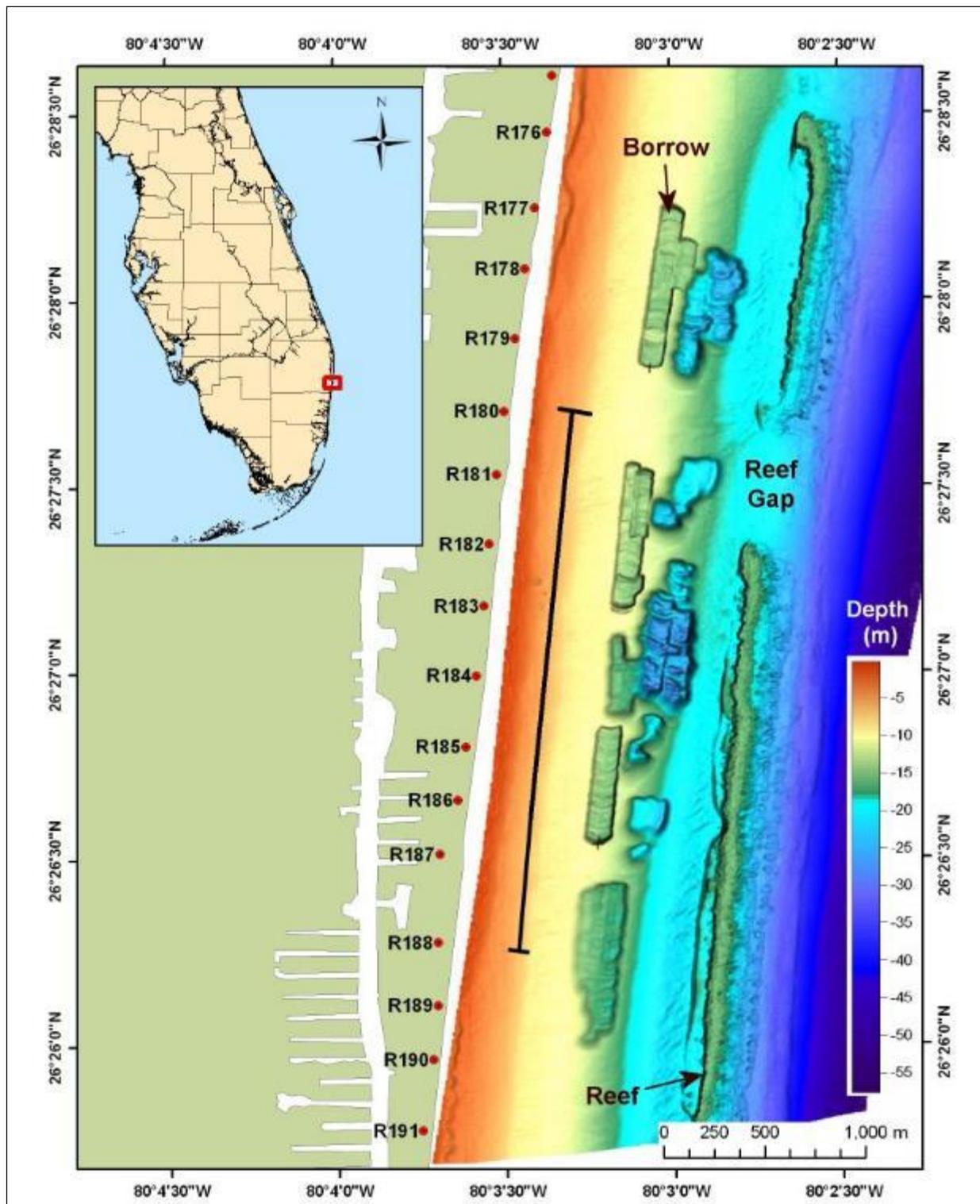


Figure 1.3. Location diagram showing a detailed bathymetry of Delray Beach and the extension of the most recent (1992, 2002, 2013) beach nourishment projects (black line). Borrow areas and the offshore shore-parallel barrier coral reefs are shown in the three-dimensional bathymetric image. The image was created based on high-resolution laser-airborne bathymetric data.

The Delray Beach nourishment program is one of the oldest nourishment programs in the state of Florida spanning more than 40 years from 1973 to the present. Florida has many beach nourishment programs on both Atlantic and Gulf coasts. The Atlantic coast has about fifty nourished areas that together received up to $65 \times 10^6 \text{ m}^3$ of sediments since the mid-1940s (Campbell and Benedet, 2004). Florida, on the other hand, has some 1300 km of sandy beaches that represent about 25% of the total U.S. sandy shores. About 368 km (30%) of Florida's beaches are in a 'critical' state of erosion (Clark, 1993). Nourished beach length in Florida in 1992 amounted to 188 km according to Clark (1993). The percentage of total sandy beach length that has been nourished is about 22% of the Florida peninsula. Other major nourishment programs aside from Delray Beach on the Florida east coast include Jacksonville Beach, Amelia Island, Jupiter Island, Boca Raton (North and South) Beach, Pompano Beach/Lauderdale-by-the-Sea, Miami Beach, *etc.*

The nourishment programs in Florida originated from erosion problems that started to become evident in the 1960s and 1970s. Several new inlets were artificially opened in the last decades in Florida. About a century ago, Florida had eleven Natural inlets along the 250 km of ocean shoreline between the Georgia border and Miami. As the decade began, around the 1920's, new inlets were opened. There are now nineteen permanent inlets along the Florida east coast. The cutting of inlets has transformed certain coastal segments into apparent "barrier islands", an artificial creation (Finkl, 1993). The cutting of inlets and construction of long jetties in some natural inlets to improve navigation conditions interrupted littoral drift and sediments supply to downdrift coastal segments, creating "sediment starved" coastal cells. Delray Beach is in one of these starved cells located between two stabilized inlets.

The town of Delray Beach was subject to heavy erosion prior to 1970 (Beachler, 1993). The revetment that the city constructed in the sixties increased erosion so that, in 1971, it was decided to nourish the beach with offshore sands. In 1973, 1.2 million m^3 of sand dredged from an offshore pit located immediately offshore of the beach was placed along 4.34 km of the city's shoreline (Figure 1.4). A picture montage of the before and after conditions in Delray Beach is shown in Figure 1.4, historic photos of the beach can be visualized in Appendix A.



Figure 1.4. Pictures illustrating the conditions of Delray Beach in 1972, before the 1973 beach nourishment project, in 1973 soon after the nourishment construction and in 2001 showing a fully restored beach with dune vegetation well established.

The placed fill in 1973 resulted in beach widths of approximately 80 m above the mean high water line. To restore dune systems and minimize aeolian transport losses, native dune vegetation was planted in 1974. By 1977, beach profile monitoring (cross-shore surveys) indicated that about 382,000 m³ of sand had eroded from the beach. The first maintenance renourishment project was constructed in 1978 (February through May) when approximately 536,000 m³ of sand was placed in two beach segments (Table 1.1., Figure 1.5). The second maintenance nourishment occurred in 1984 (September and October) when approximately 994,000 m³ were placed over the original 4.3

km of beach. A monitoring report (CPE, 1992) indicated that by October 1992, about 260,000 m³ of the fill placed in 1984 had eroded from the beach.

In an effort to address this erosion, a third maintenance renourishment occurred in 1992 (November and December) from R180 to about 150 m south of R-188 (the 1992 nourishment limits is shown in Figure 1.2. by a black line). Approximately 914,000 m³ of sand was placed along 2.7 km of beach. A fourth maintenance nourishment occurred in 2002 (February and March) from 150 m north of R180 to 150 m south of R188 when approximately 940,000 m³ of sand was placed along 3 km of beach. A smaller emergency restoration project that used about 191,000 m³ of sand was also constructed in early 2005 to mitigate for sediment losses caused by two hurricanes that affected the project area in September and October of 2004 (H. Frances and H. Jeanne). The last beach renourishment occurred in 2013 where 813,000 m³ of sand was placed along 3500 m of beach.

Table 1.1 Volumes placed on Delray Beach between 1973 and 2013.

Year	Volume (m ³)	Length (m)	Fill Density (m ³ /m)	Fill Limits
1973	1,250,000	4,270	293	R175 to R188
1978	536,000	2,890	185	R176 to R182 and R186 to R188
1984	994,000	4,270	233	R175 to R188
1992	914,500	2,730	334	R180 to R188.5
2002	940,000	3,000	313	R179 to R188
2005*	191,000	3960	48	R175 to R188
2013	885,700	3500	253	R179 to R188

*Hurricane impact mitigation project.

Since inception of the nourishment program in 1973, about 5,711,000 m³ of sediments were placed on Delray Beach. The initial project employed an initial volume placement ‘density’ of 293 m³/m and a volume of 1.2 million m³ (Table 1.1), and from 1978 to 2013 the program has been maintained with an average volume placement of 130,000 m³/yr. The interval between renourishments has been gradually increasing from 5 (initial renourishment) to 10 years in average, with exception of the smaller emergency restoration project conducted in 2005 as a response to episodic storm erosion caused by Hurricanes Frances and Jeanne.

Previous studies indicate that the volume changes post-nourishment at Delray Beach varies greatly in the alongshore direction and there are clear occurrences of persistent erosional hot spots within the project limits (*i.e.* Fernandez, 1999, Gravens (1997), Beachler, (1993), and CPE (1994, 1995, 1996, 1998, 1999 and 2001), Hartog et al., 2007, Benedet *et al.*, 2006, 2007, 2013), Benedet & List (2008).

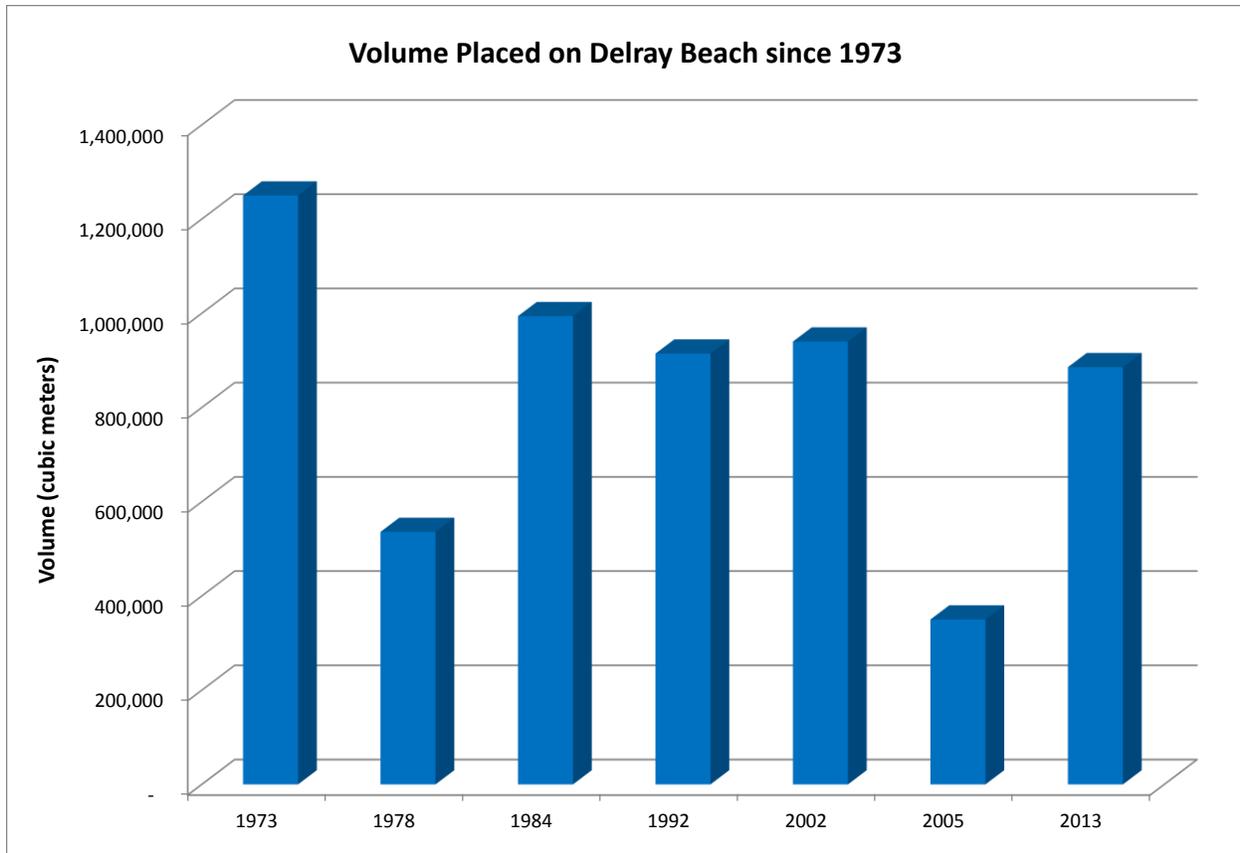


Figure 1.5. Volumes placed on Delray Beach since start of the nourishment program in 1973.

Multiple hypotheses have been raised to explain the observed erosion hot spots (EHS) on this beach nourishment project over the last couple decades. Predictions of a one-line shoreline change model were compared with measured shoreline between 1987 and 1992 by Gravens (1997). The coastal segment between R180 and R181 was defined as an EHS by this author. Gravens (1997) hypothesized that the EHS near R181 may be related to a gap in the barrier reef system located directly offshore of this beach segment. Theoretically, the gap would cause gradients in nearshore wave height that would induce gradients in alongshore transport that could in turn lead to aggravated erosion and erosion hot spot (EHS) development.

Project performance and development of EHS from 1975 to 1998 and 1975 to 1990 were evaluated by Fernandez (1999) using a simplified shoreline change simulations compared with the measured shoreline change data. The beach segment near monument R178 was identified as a cold spot (segment that experiences more accretion than predicted), and an EHS was identified at profile monument R187. Finer sand in the south end of the project was suggested as a potential cause for the EHS at R187 by this author.

Numerous monitoring reports (CPE, 1994, 1995, 1996, 1998, 1999 and 2001) indicate greater shoreline recession near R186 and R187. In an effort to emphasize the greater magnitude of erosion in this area, CPE (1995) reported that while the mean shoreline retreat of the fill was about 19 m, the area at R187 receded approximately 56 m since construction. Greater erosion at R187 was qualitatively attributed to the extra amount of fill placed at this location and to fill end losses (lateral diffusion of Dean and Yoo, 1992). Higher rates of erosion near R181 and R183 are reported

in 1995 but discontinued in subsequent years (CPE, 1994, 1995, 1996, 1998, 1999, and 2000). Segments 500 m up and downdrift of the nourishment area accreted slightly during most of the monitored periods.

In Summary, multiple studies that evaluated different time-periods of beach nourishment performance, including this thesis, report that the beach around profile monument R178 (just north of the beach fill project) is relatively stable and wide, the beach extension between R184 and R185 is classified as an accretion cold spot (a stable or accretion zone) and there are trends of accentuated erosion both in north (R180-R181) and south (R186-R188) sides of this cold spot. In the region between R186 and R188 the erosional trend is more pronounced, being considered a prominent hot spot (EHS) of erosion by Benedet *et al.* (2007)) (Chapter 2 of this thesis). This zone extends for approximately 600 m alongshore. About 50% of total erosion losses from the project area after the 1992 beach nourishment project, for example, occurred within this erosional hot spot (Benedet *et al.*, 2007).

This trend of stability north of the fill, accentuated erosion at R180-R181, stability at R184-R185 and aggravated hot spot erosion at R186-R188 continues to this day as evidenced by CPE (2013). In Figure 1.6 it can be noticed that in 2013, 11 years after the last major renourishment, the beach berm crest was located seaward of the design beach at monuments R183-R184-R185 (stable segment), landward of the design, violating design conditions, in the surroundings of R181 (erosional segment) and abruptly landward of the design beach in the beach segment between R186-R188 (erosion hot spot). At the very end of the fill (R188) and immediately downdrift of it (R189, R190) the berm crest is practically at the erosion control line (limit between private property and state property – public beaches) indicated the critical erosional situation of this beach segment. The location of the post construction berm after the construction of the 2013 beach renourishment project is also shown in Figure 1.6. Analysis of the post-construction berm position demonstrates that the strategy adopted to address additional erosion at the EHS beach segment is to place more fill in the location, a strategy that is been using the past few renourishment events (it was also used in 2002).

Delray Beach is an example of a successful beach nourishment program, the City of Delray beach currently has a healthy restored beach-dune system that would otherwise have been vanished if were not for the nourishment efforts. However, prominent hot spot erosion persist causing increased annual volumetric requirements to maintain the beach nourishment program. With high nourishment maintenance volumes and scarce sand resources along the SE Florida coast the future of the program may be threatened. Thus there is a need to investigate engineering design optimization strategies that can reduce annual volume requirements of the nourishment program, reduce public spending and ensure a stable beach system for the future generations.

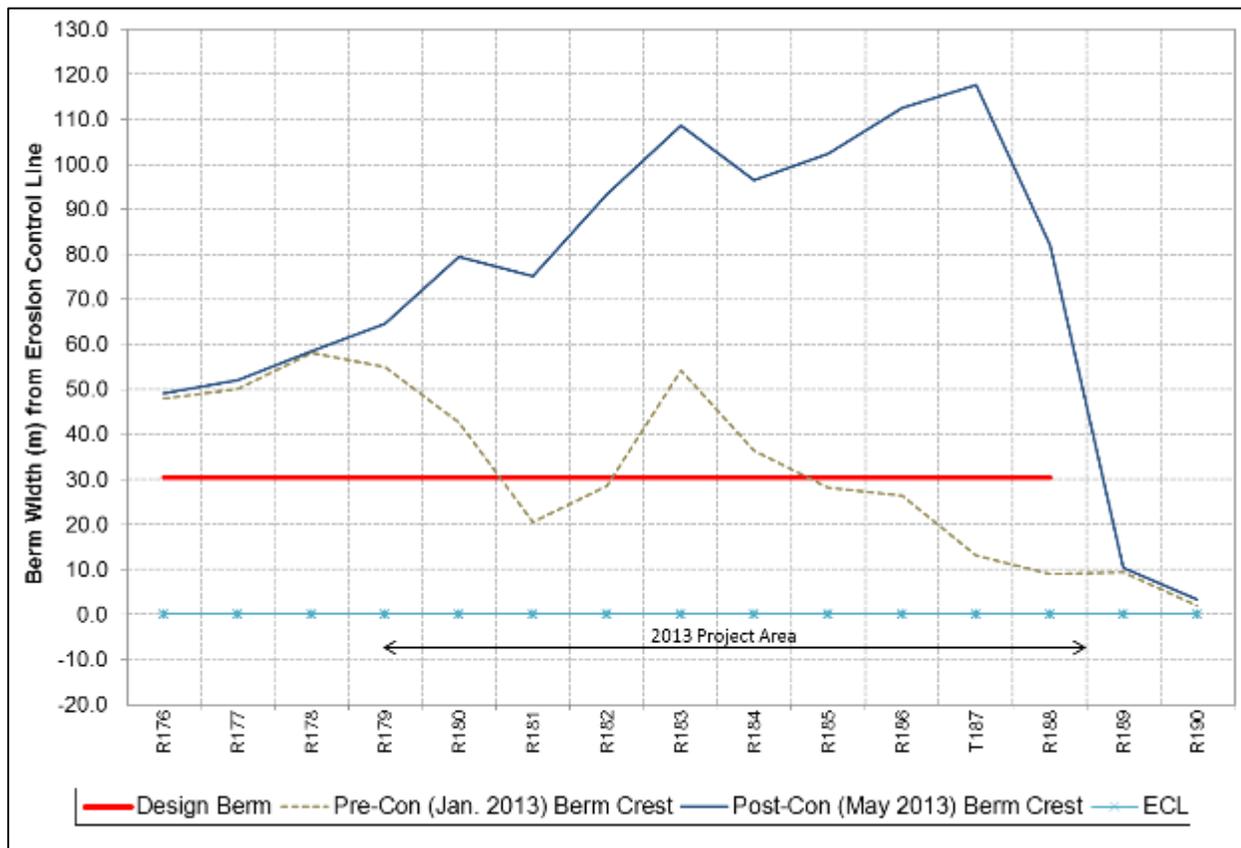


Figure 1.6. Berm crest (+2.4m NAVD) position before and after the 2013 beach renourishment project compared to the design berm location and the ECL (erosion control line).

Several hypotheses have been raised by different authors in the past to explain the development and persistency of erosional hot spots on this project. Hypothesis include effects of offshore gaps in the shore-parallel reef system on incoming waves (Gravens, 1997), sediment grain size distribution (Fernandez, 1999), fill diffusion end losses (CPE, 1994, 1995, 1996, 1998, 1999 and 2001). It is interesting to note is that none of these authors investigated the effects of the large dredge pits located immediately offshore of the beach fill (Figure 1.1.). Delray beach provides an amazing natural laboratory to investigate dredge pit effects on nearshore hydrodynamics since there are prominent pits located directly offshore of the project site with varying dimensions (size, cut depth, geometrical form). Offshore dredge pits were not investigated by previous authors probably due to the absence of detailed nearshore bathymetric data at the time of these earlier works. In this thesis the hypotheses raised by earlier authors, and others such as dredge pit effects, are further investigated using measured data and morphological modeling.

1.3. PURPOSE AND GOALS

The main purpose of this thesis is to understand the processes behind the development of persistent erosional hot spots within the geographical boundaries of the Delray Beach nourishment project. This understanding will, in turn, enable the design of targeted engineering interventions aimed at reducing the annual volumetric losses of this nourishment program.

The specific purposes of this thesis are to:

- (1) Evaluate the performance of the Delray Beach nourishment project with focus on identification of erosion hot spots and cold spots.
- (2) Understand the physical processes driving project performance at Delray Beach and causing the formation of erosion hot spots.
- (3) Study beach response to offshore dredge pits and dredge pit design parameters using a natural laboratory (Delray Beach) and hypothetical model tests inspired by the Delray Beach case.
- (4) Evaluate engineering interventions designed to reduce volumetric losses from the project site and improve overall project performance.

1.4. HYPHOTHESES

In this thesis the following hypothesis are tested:

1. The erosion hot spot at the south end of Delray Beach are caused by the fill influence on beach planform (shoreline orientation) that causes increased localized alongshore transport rates also referred to as 'fill lateral diffusion' or 'fill end losses'.
2. The erosion hot spots and the overall alongshore variability of the Delray Beach nourishment performance is caused by differences in alongshore grain size distribution.
3. The erosion hot spots and the overall alongshore variability of the Delray Beach nourishment performance is caused by offshore bathymetric features such as offshore reef gaps and dredge pits.
4. Offshore dredge pits can be designed to have minimum or no adverse impact on adjacent shorelines.
5. Volumetric losses from the Delray Beach nourishment project can be greatly reduced with minimum downdrift impacts by engineering interventions such as manipulation of offshore bathymetry and/or strategic placement of structures.

1.5. STUDY AREA REGIONAL FRAMEWORK

1.5.1. Geology and Geomorphology

Delray Beach is situated in SE Coast of Florida, in Palm Beach County. Palm Beach County is delimited to the north by Martin County line and in the south by Broward County line (Figure 1.7).

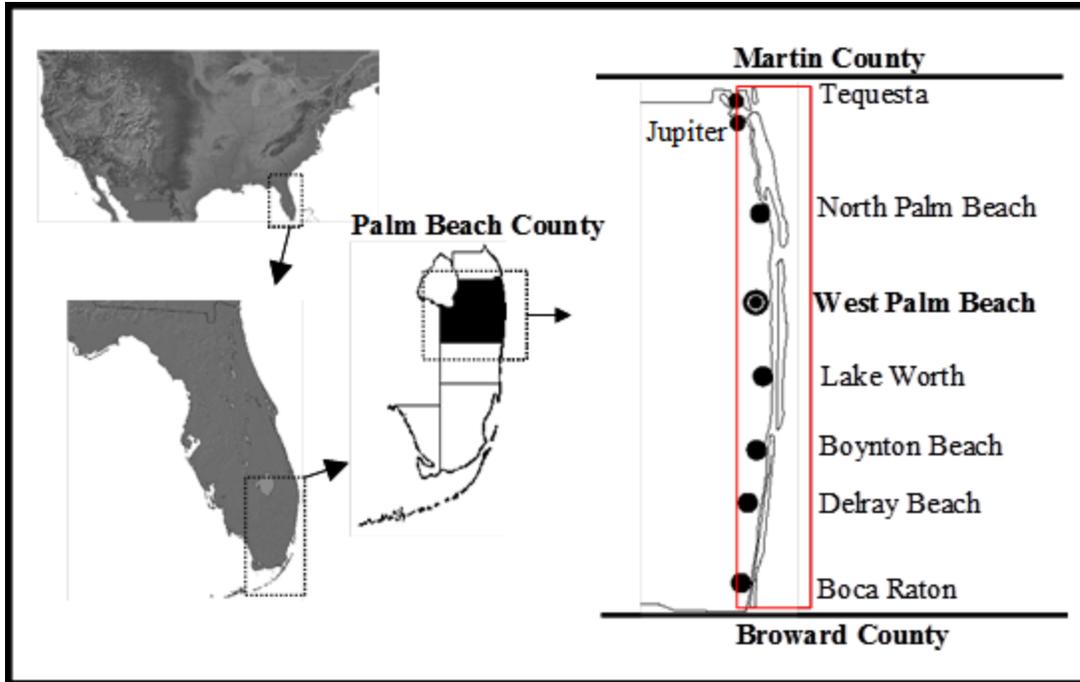


Figure 1.7. Location diagram for Palm Beach County, Florida. Close up showing the study area and major urban centers (not to scale)

Southeast Florida is part of the Florida Peninsula, which is a large carbonate platform containing a thick sedimentary sequence that was constructed generally from the Jurassic (Mesozoic Era) to the Miocene (Cenozoic Era) (viz. from about 180 to 5 million years ago) (Davis, 1997). Carbonate, evaporite, and siliclastic sediments began to accumulate over basement rocks consisting predominantly of late Triassic – Early Jurassic mafic volcanic suites (Winston, 1971) on what eventually became the Florida Peninsula, which was associated with the development of the Gulf of Mexico basin of deposition, probably in the early Jurassic (Winston, 1992). The geological development of the southeast Florida coast was strongly influenced by pre-Holocene topographic highs upon which coastal barriers were built (Finkl, 1993; Hoffmesiter et al., 1967), providing a stable base where sediments could accumulate as sea level rose in the mid-Holocene.

The major global eustatic sea-level lowstand that occurred during the late Oligocene and early Miocene in response to a global cooling trend, and which was one of the most rapid and profound drops in the world sea level (see, for example, Finkl and Fairbridge, 1979; Fairbridge and Finkl, 1980), had a profound influence on marine carbonate rocks in Florida. Lowered sea levels subjected these rocks to non-marine phreatic and vadose hydrologic conditions and induced increased erosion due to lowered base levels to which rivers grade. Surface water runoff physically and chemically eroded (dissolved) much of the early Oligocene rocks from positive areas. Extensive groundwater dissolution created cavern system in Eocene and older rocks, precursors to the karst terrain that later developed. Neogene marine transgressions resulted in filling and burial of many of these cavernous areas by generally fine-grained sediments that were reduced from the calcareous platform rocks or accumulated from eolian accretion. In places, these infilling sediments included concentrations of marine and non-marine vertebrate fossils (Randazzo, 1997) that significantly increased particle size. Dissolution of Florida's carbonate rocks produced significant changes in rock fabric, accompanied by development of many different types of pore

spaces. Moldic, vugh, and interparticle pore types are most common and give the carbonates a honeycomb or labyrinth habit to produce porous, sharp-edged, and irregular surfaces. Extensive dissolution created larger cavities such as caves and caverns as well as sinkholes and karst landscapes (Randazzo, 1997). When eroded by marine processes, the carbonate rocks of the porous and solution-holed seafloor produce gravel sized fragments that are commonly washed up on beaches after storm (Hine et al., 1998). The rock cored sedimentary accumulations were bypassed with bays and estuaries forming on the landward sides of spits, islands and bars. The lithified remains of older shorelines associated with lower stands of Pleistocene sea level also served as traps for coastal sediments driven shoreward by Holocene sea-level rise.

The present natural shoreline consists of one to two meters of beach sand that overlies lithified sands, beach rocks, and coquina, belonging to the Anastasia Formation (Duane and Meinsbruger, 1969; Finkl, 1993). Rock outcrops of the Anastasia are common along the coast at about the mean tide level, but there are notable outcrops at one or two m above sea level, as well as underwater where they form hardgrounds (Finkl, 1994). The submerged paleoshorelines form rocky reef system well known by scuba divers and sports fisherman. These shore-parallel “reefs” (comprised by rock and coral-algal components) system, composed of inshore exposure of the Pleistocene Anastasia Formation (a cemented, quartzitic, molluscan grainstone that formed in beach and shallow-water nearshore environments) (Stauble and McNeil, 1985) and coral-algal reef tracts (referred to as the Florida Reef Tract) (Lidz et al., 1997), increases in depth offshore as a giant staircase, forming distinct tracks as the first (0.1 to 2 m), second (3-6 m), and third (8-10 m) reefs. The parabathic reef tracts cross the study area and extend southwards into the Florida Keys and represent approximate positions of paleoshorelines extensionally offshore and vertically within particular tracts as prior sea-level stands were revisited through time (Finkl, 1993, 1994). Sedimentary troughs that contain admixtures of clean, free-running sands, discontinuous lenses or stringers of silts and clays separate the reef tracts, or carbonate rubble accumulations deposited in association with paleo-inlets that cut through the reef tracts (Duane and Meisburger, 1969; Finkl, 1993; Finkl, in press).

A general characteristic of the southeast Florida continental shelf includes a narrowing from the north to south, at least to the Lake Worth Inlet, where it narrows to a nearly constant width of about 2900 m (Duane and Meisburger, 1969; Finkl, 1993).

The study area is commonly referred to as a Barrier Island coast, but many of the so-called barrier islands are actually, barrier spits which were truncated by human intervention (Finkl, 1993). About a century ago, Florida had eleven natural inlets on 585 km of shoreline, between the Georgia border and Miami. After 1920, several new inlets were opened and many of these in the study area such as Lake Worth inlet opened in (1920). There are now nineteen inlets in the same stretch of coastline (Finkl, 1993). The Anastasia Formation is the rock core of the many newly created “Barrier Islands”. The bedrock geology influences the morphology of the coastal zone in many different ways (Finkl and da Prato, 1994; Brown, 1999). Bedrock of the Anastasia Formation is exposed onshore or buried at a shallow depth below present-day beaches (Figure 2). Most beach berm contain beach sands less than 2 m in thickness so that some beaches are stripped of sediment during storm to expose the underlying bedrock during part of the year (Finkl, 1994). Dunes fronting back beaches were commonly leveled for high-rise development so that today, incipient dunes only develop where buildings or infrastructure is setback from the shore. Seawalls that preclude dune formation back many beaches along this developed shore.

1.5.2. Wind, Waves & Tides

The open-ocean, subtropical southeast coast of Florida is affected by nor'easters (winter cyclonic northeasterly cold fronts), tropical southeast trade winds, tropical storms and hurricanes that collectively comprise the meteorological systems that influence the wave climate in the study area. Predominant wind direction is from southeast and southwest during northern hemisphere summer months and from the northeast during winter (Davis, 1997). These general patterns are occasionally interrupted by extreme meteorological events such as tropical storms and hurricanes. During the last century, southern Florida has been affected by more hurricanes than any other area of comparable size in the United States (Dohering *et al.*, 1994). In 2004, for example, four hurricanes hit the State of Florida, three were major hurricanes and two affected the study area. Nor'easters (winter extra-tropical storms) are significant weather-wave events that cause considerable amount of sediment transport. Although wind velocities in nor'easters are typically below hurricane force (*i.e.* less than 120 kph), they persist for several days (up to a week) generating large swell waves (2-3 m) with relatively long periods (10-12 s). By comparison, hurricanes are more severe in terms of wind speed and storm surge but the shoreline impacts tend to be confined to coastal segments on the order of 100 km; waves tend to be steep with shorter periods (4-8 s) and Hurricane events have relative shorter duration compared to nor'easters. Wave conditions associated with nor'easters and hurricanes account for most of the sediment removal in the Delray Beach area. Because nor'easters occur more frequently than hurricanes and are more persistent, they figure more prominently in the characterization of long-term morphodynamics at Delray Beach.

Calculation of wave statistics were based on the analysis of 20 years of hourly wave records from the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory wave hindcast for Wave Information Study (WIS) Station A2011, which is located approximately 6 km northeast of Delray Beach at 90 m water depth. The average deepwater wave height is 1 meter with a period of 8.0 s, and an angle of approach from the east-northeast (64°). Excluding extreme events (hurricanes and tropical storms), higher waves with longer peak periods (*i.e.* 10 to 12 s) occur from October through March with predominant wave directions from northeast to east-northeast. Between April and September, waves approach mostly from the east and southeast with shorter periods (3-6 s). Tides are semidiurnal, mean water level is at 0.52 meter and average tidal amplitude is about 0.4 m. Episodic fluctuations in water levels occur due to storm surges induced by extreme weather events (tropical storms, hurricanes and to a lesser extent nor'easters).

1.6. THESIS ORGANIZATION

This thesis is organized in 7 chapters. Chapter 1 is the introductory chapter containing the descriptions of the nourishment practice in the USA and the nourishment program of Delray Beach, study area characterization, study objectives and hypothesis. The chapter utilizes information from cited literature and also relies heavily on the analysis of the annual monitoring reports issued by Coastal Planning & Engineering Inc. (CPE) and the work of Benedet *et al.* (2004) and Finkl and Benedet (2006). A compilation of information about the nourishment program is given in chapter one to provide a general overview of the project area to the reader and set the framework for the following chapters.

Chapter 2 is based on Benedet *et al.* (2007). In this chapter a detailed analysis of the performance of the Delray Beach 1992 beach nourishment project is conducted using measured data aided by numerical modeling results. A quantitative definition for erosion hot spots is developed and the area at the southern end of the project, between profile monuments R186 and R187 is classified as an erosion hot spot. The hypothesis that alongshore grain size distribution is the main cause for the erosional hot spot at the south end of the Delray Beach nourishment project is ruled out in this chapter because data from multiple annual monitoring reports from Coastal Planning & Engineering Inc. (now CB&I) demonstrated that alongshore grain size distribution on Delray Beach varies greatly from year to year, and there is no persistent trend of finer grain sizes being located in the erosional hot spot segment compared to the rest of the beach. At this earlier stage there was not enough evidence to identify which particular phenomena was the main cause of the erosion hot spot and it is suggested that it is likely to be due to a combination of nearshore bathymetry effects (dredge pits) and shoreline orientation post fill construction that induce fill end losses.

Chapter 3 is based on Benedet et al (2006) and Hartog et al (2008). In this chapter the numerical modeling results presented of chapter 2 are refined based on upgrades to the Delft3D model, better input bathymetry and a sensitivity analysis of the important of physical processes is conducted to investigate hypotheses raised in chapter 2 to explain nourishment performance and erosion hot spot development. Numerical modeling simulations on this chapter are able to rule out the effect of offshore reef gaps as causes for hot spot erosion. It suggests that the main drivers of beach performance are offshore dredge pits due to its large effects on incoming waves and changes in shoreline orientation caused by the fill. Simulations of morphology evolution for periods of one year were performed in this chapter, however, these simulations showed strong sensitivity to changes in sequencing of the developed annual wave climate and a detailed study of wave climate schematization at the study area was recommended. An in-depth analysis of the relative effects of shoreline orientation changes at the southern end of the fill and alongshore wave height gradients induced by the offshore borrow pits on hot spot development was also recommended.

Chapter 4 is based on the work of Benedet & List (2008). In this chapter the physical processes responsible for erosion hot spot development are finally distinguished and explained in detail utilizing a flow momentum balance approach. By isolating the force components of the alongshore currents it could be identified that the alongshore pressure gradients (resulting from alongshore variations in wave setup due to dredge pit effects) was the main force responsible for an acceleration of the alongshore currents (and consequently sediment transport) downdrift of the dredge pits, causing a sediment imbalance (more sediment leaving the beach segment than entering it) and hot spot development. Morphology simulations conducted for bathymetric scenarios without the deep dredge pits showed a significant reduction in erosion at this beach segment supporting the inference that the dredge pits, especially the deeper dredge pits dredged in the 1970s and 80s, are the drivers of erosion hot spot development at the Delray Beach.

Chapter 5 is an investigation of the influence of dredge pit design criteria (cross-shore and alongshore length, cut depth, distance from shore) on the magnitude of effects on incoming waves and changes of adjacent beaches. Strong effects of the offshore dredge pits on beach changes were observed in the Delray Beach. It was also observed that the dredge pits located offshore of Delray Beach have very distinct design characteristics, causing very different level of impacts on incoming waves and beach response. With that observation consolidated, it was decided to further

investigate how the dredge pit design parameters play a role in the magnitude of its effects on adjacent beaches. The investigation was conducted utilizing a schematic morphological model setup where hundreds of model runs could be performed to evaluate dredge pits with different shape, size, location and depth of cut. It was found that depth of cut and cross-shore length are the main parameters influencing the magnitude of effects of dredge pits on incoming waves and consequently adjacent beach changes. Based on the results of the investigation conducted in this chapter, design guidance for dredge pits is provided when reduction of adverse effects on adjacent beaches is desired.

In chapter 6, following the recommendation of chapter 3, an in-depth study of methods of wave climate schematization applied to the study area was conducted to improve numerical modeling morphological predictions at the study area while at the same time optimizing computational time. Five wave climate schematization methodologies were evaluated and a wave climate schematization that reproduces the main features of the project area was selected to investigate possible design modifications aimed at reducing volumetric losses and eliminating the erosional hot spot at the south end of Delray Beach. Engineering interventions such as backfilling of the dredge pits and placement of a breakwater or other permeable structure (*i.e.* submerged reef) at the sound end of the fill were found to reduce nourishment volume losses by half with varying levels of impacts on the shorelines immediately downdrift of the beach fill. A recommendation to conduct detailed feasibility study (cost, benefit, and environmental impacts) prior to implementing any of the engineering interventions evaluated is provided.

Chapter 7 is the conclusion and recommendations chapter where the main findings of this study are summarized and recommendations for future work are provided.

CHAPTER 2. IDENTIFICATION OF EROSIONAL HOT SPOTS ON THE DELRAY BEACH NOURISHMENT PROJECT

Abstract

Beach erosion, a problem along most sandy shores, can be caused by man-induced interventions to the coast or natural processes. Remediation of beach erosion (*i.e.* beach restoration) along eroding developed beachfronts is commonly practiced in the U.S. by periodic beach renourishment with or without coastal structures. Rates of erosion within beach fills generally vary greatly and areas that erode faster than the nourishment average are commonly termed ‘erosional hot spots’ (EHS). Delray Beach, located on the southeast coast of Florida, was renourished for the fourth time on December of 1992 with about 914,000 m³ of sand dredged from offshore and placed along 2.7 km of beach. About 448,000 m³ of the fill had eroded away by 2001, about eight and a half years after initial construction. Two beach segments with higher erosion rates higher than the nourishment average were identified based on analysis of annual beach profile data. About 40% of the eroded volume accrued from one of these beach segments, a 600-m long erosional hot spot (EHS), located on the downdrift end of the nourishment. Hypothesis to explain EHS development were evaluated, these included the influence of nearshore features (reefs and borrows) on nearshore wave propagation, variability of grain size alongshore, and changes in shoreline orientation induced by the placement of fill. The nearshore reefs have little to negligible influence on the nearshore waves and are not the cause of the EHS. Borrow areas significantly influence nearshore waves in some segments of the beach; however its effects are not significant in the EHS segment. Grain size differences alongshore were also not the cause of increased erosion of EHS segments since grain sizes are not persistently finer where higher erosion is observed or vice-versa. Change in shoreline orientation in the south end of the fill (EHS segment) causes an acceleration of the alongshore currents and an increase in sediment transport potential, shoreline orientation effects play a relatively more significant role in the development of the EHS in the south end of the fill than the other processes evaluated.

This chapter is based on:

Benedet, L., Finkl, C.W., and Hartog, W.M., (2007) *Journal of Coastal Research*, 23(1), 33-48.

2.1. INTRODUCTION AND OBJECTIVES

Beach erosion and shoreline recession are major problems along most developed sandy shores. Remediation of beach erosion (*i.e.* beach restoration) along eroding developed beachfronts is commonly practiced by combinations of periodic renourishments with or without coastal structures to stabilize a beach over the long term. Although beaches can be restored in many ways, beach nourishment is the most commonly practiced method of shore protection in both the U.S. and Europe (NRC, 1995; Finkl and Walker, 2002; Hanson *et al.*, 2002).

Properly planned beach restoration requires quantitative assessment of nourishment evolution and an understanding of the main processes that affect fill performance. Additional attention is generally given to erosional hot spots (EHS) because they erode more quickly than the alongshore-average rate of erosion of the placed fill and can negatively impact a beach nourishment project.

Analysis of monitoring data (1992 to 2001) for a renourishment at Delray Beach, southeast coast of Florida (Figure 1), provides a rational basis to explain post-placement fill performance and EHS development. Delray Beach was initially nourished in July 1973 with the placement of 1.25 Mm³ of sand and has been renourished five times since then (1978, 1984, 1992, 2002 and 2005). The 2005 nourishment was a smaller emergency project designed to mitigate for volume losses attributed to two hurricanes that affected the project area. Data from pre- and post-construction and annual monitoring surveys of beach profiles and beach sediments after the 1992 nourishment are analyzed in detail in this manuscript. Beach profiles are used to analyze beach nourishment evolution and volumetric losses and to identify EHS. Possible mechanisms that cause EHS are evaluated in terms of wave transformation over bathymetric irregularities, alongshore grain-size distribution, and shoreline orientation.

The main objective of this study is to identify the processes that affect development of EHS in the nourishment area. Specific objectives include: (1) identification and differentiation of EHS within a beach fill using quantitative parameters, (2) Evaluation of the effects of wave transformation over bathymetric irregularities, alongshore grain-size distribution patterns and shoreline orientation on nourishment erosion, and (3) development of a framework for future, more detailed, numerical modeling studies.

2.2. STUDY AREA LOCATION AND GEOMORPHODYNAMIC FRAMEWORK

Delray Beach is located in southern part of Palm Beach County about 80 km north of Miami Beach on the Florida southeast coast. Nearby inlets include south Lake Worth Inlet 10 km to the north and Boca Raton inlet 13 km to the south (Figure 2.1). The locations of beach profile monuments are indicated in Figure 1 by red bullets. The beach profile monuments defined by the Florida Department of Natural Protection (FDEP) are spaced approximately 300 m apart. The study area embraces the beach between profile monument R180 to the north and R188 to the south.

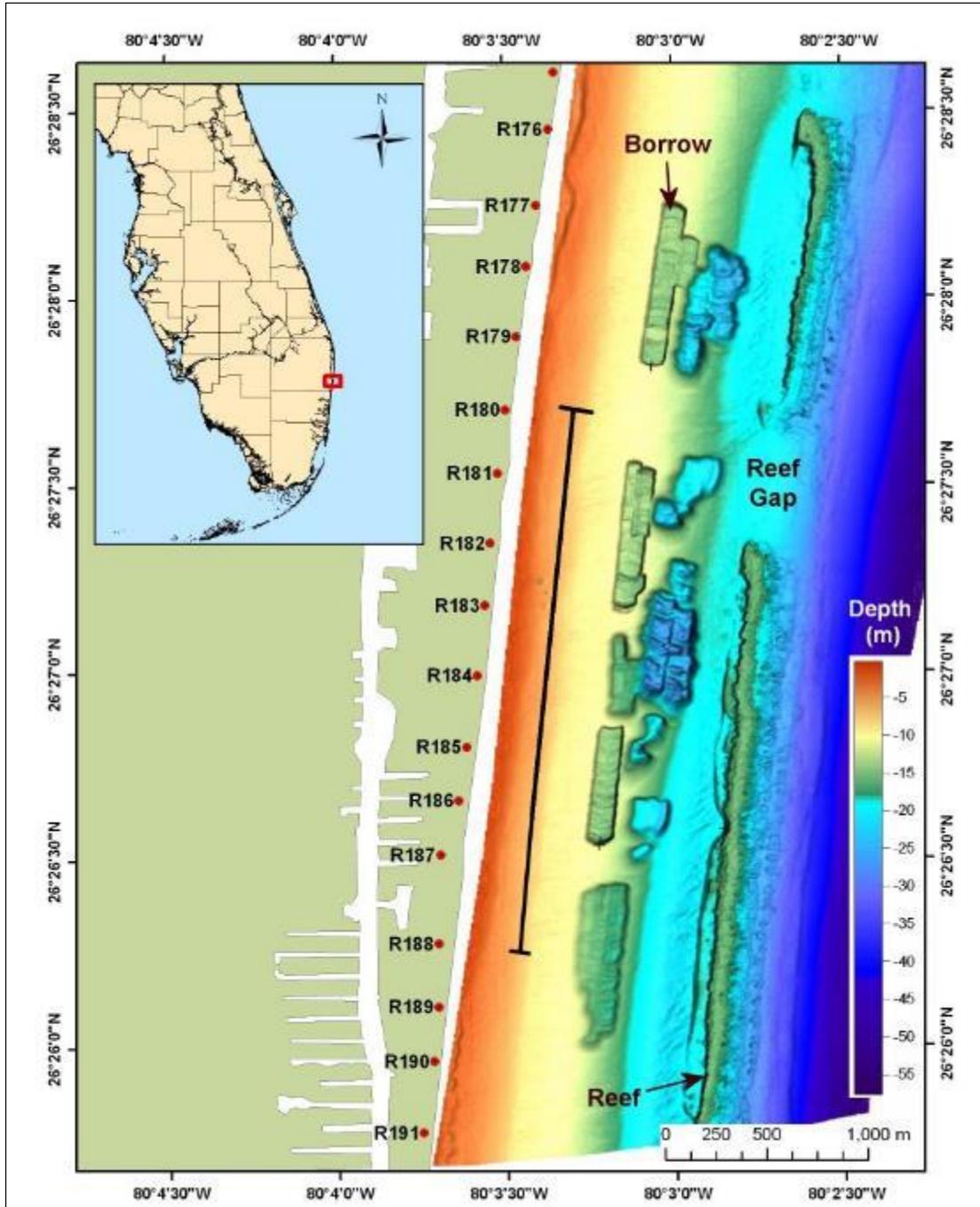


Figure 2.1. Location diagram showing bathymetry and nourishment boundaries of the study area. Borrow areas and the offshore shore-parallel barrier coral reefs are shown in the three-dimensional bathymetric image. The image was created based on high-resolution laser-airborne bathymetric data.

2.2.1. Geological Controls on Coastal Geomorphology Processes

Delray Beach, located in coastal southeast Florida, occurs on the Florida Peninsula, a large carbonate platform containing a thick sedimentary sequence that was constructed generally from the Jurassic to the Miocene (viz. from about 180 to 5 million years ago) (Davis, 1997). Geological development of the southeast Florida coast was strongly influenced by pre-Holocene topographic highs upon which coastal barriers were built (Hoffmesiter *et al.*, 1974; Finkl, 1993), providing a stable base where sediments could accumulate as sea level rose throughout the post-glacial period.

When eroded by marine processes, the sandstones and coquina of the Anastasia Formation and coral reefs produce gravel sized fragments that are commonly washed up on beaches after storms (Hine *et al.*, 1998). These carbonate sediments mix with siliciclastic sediments to form the suite of observed beach sediments.

The present natural shoreline contains one to two meters of beach sand that overlies partly lithified sediments of the Anastasia Fm. (Finkl, 1993). Outcrops of the Anastasia Fm. occur underwater where they form nearshore hardgrounds or rock reefs (Finkl, 1994) that serve as benthic habitats. Offshore barrier coral reef systems comprise the northern-most extension of the Florida Reef Tract (Lidz *et al.*, 1985) that is best developed along the Florida Keys. In the Delray Beach study area, these barrier reefs typically occur at depths of 18 to 22 m. Additional reef tracts occur farther offshore at greater depths. Sedimentary troughs located between the beach (or nearshore rock reefs) and the offshore coral reefs are infilled with sandy sediments that have been used as borrow materials for Delray Beach nourishments (*e.g.* Finkl *et al.*, 2003). Coarser sediments (carbonate rubble accumulations) are located adjacent to reef gaps (holes, former passes and inlets, in the barrier reef system) and as overwash fans on the leeward sides of the barrier reefs (Finkl *et al.* 2005).

2.2.2. Wind, Waves and Tides

The open-ocean, subtropical southeast coast of Florida is affected by nor'easters (winter cyclonic northeasterly cold fronts), tropical southeast trade winds, tropical storms and hurricanes that collectively comprise the wave climate in the study area. Predominant wind direction is from southeast and southwest during northern hemisphere summer months and from the northeast during winter (Davis, 1997). These general patterns are occasionally interrupted by extreme meteorological events such as tropical storms and hurricanes. During the last century, southern Florida has been affected by more hurricanes than any other area of comparable size in the United States (Dohering *et al.*, 1994). In 2004, for example, four hurricanes hit the State of Florida, three were major hurricanes and two affected the study area. Nor'easters (winter extra-tropical storms) are significant weather-wave events that cause considerable amount of sediment transport. Although wind velocities in nor'easters are typically below hurricane force (*i.e.* less than 120 kph), they persist for several days (up to a week) generating large swell waves (2-3 m) with relatively long periods (10-12 s). By comparison, hurricanes are more severe in terms of wind speed and storm surge but the shoreline impacts tend to be confined to coastal segments on the order of 100 km; waves tend to be steep with shorter periods (4-8 s) and Hurricane events have relative shorter duration compared to nor'easters. Wave conditions associated with nor'easters and hurricanes account for most of the sediment removal in the renourished area. Because nor'easters occur more

frequently than hurricanes and are more persistent, they figure more prominently in the characterization of long-term morphodynamics at Delray Beach.

Calculation of wave statistics were based on the analysis of 20 years of hourly wave records from the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory wave hindcast for Wave Information Study (WIS) Station A2011, which is located approximately 6 km northeast of Delray Beach at 90 m water depth. The average deepwater wave height is 1 m with a period of 8.0 s, and an angle of approach from the east-northeast (64°). Excluding extreme events (hurricanes and tropical storms), higher waves with longer peak periods (i.e. 10 to 12 s) occur from October through March with predominant wave directions from northeast to east-northeast. Between April and September, waves approach mostly from the east and southeast with shorter periods (3-6 s). Tides are semidiurnal, mean water level is at 0.52 meter and average tidal amplitude is about 0.4 m. Episodic fluctuations in water levels occur due to storm surges induced by extreme weather events (tropical storms, hurricanes and to a lesser extent nor'easters).

2.3. HISTORY OF BEACH NOURISHMENT AT DELRAY BEACH

Since 1973, the study area was renourished five times with a cumulative total of 4.5 Mm³ of sand (Table 2.1). Initial nourishment sediment, dredged from an offshore borrow pit (July 1973) comprised 1.25 Mm³ of sand placed along 4.3 km of beach. The placed fill resulted in beach widths of approximately 80 m above the mean high water line. To restore dune systems and minimize aeolian transport losses, native dune vegetation was planted in 1974. By 1977, beach profile monitoring (cross-shore surveys) indicated that about 382,000 m³ of sand had eroded from the beach. The first maintenance renourishment project was constructed in 1978 (February through May) when approximately 536,000 m³ of sand was placed in two beach segments.

The second maintenance renourishment occurred in 1984 (September and October) when approximately 994,000 m³ were placed over the original 4.3 km of beach. A monitoring report (CPE, 1992) indicated that by October 1992, about 260,000 m³ of the fill placed in 1984 had eroded from the beach.

In an effort to address this erosion, a third maintenance renourishment occurred in 1992 (November and December) from R180 to about 150 m south of R-188 (Figure 2). Approximately 914,000 m³ of sand was placed along 2.7 km of beach. A fourth maintenance nourishment occurred in 2002 (February and March) from 150 m north of R180 to 150 m south of R188 when approximately 940,000 m³ of sand was placed along 3 km of beach. A smaller emergency restoration project that used about 350,000 m³ of sand was also constructed in early 2005 to mitigate for sediment losses caused by two hurricanes that affected the project area in September and October of 2004 (H. Frances and H. Jeanne).

Table 2.1. Delray Beach nourishment history of volume placement.

Year	Volume (m ³)	Length (m)	Density (m ³ /m)
1973	1,250,000	4,270	293
1978	536,000	2,890	185
1984	994,000	4,270	233
1992	914,500	2,730	334
2002	940,000	3,000	313
2005*	350,000	-	-

*storm emergency restoration, approximate volume.

In an effort to address this erosion, a third maintenance renourishment occurred in 1992 (November and December) from R180 to about 150 m south of R-188 (Figure 2). Approximately 914,000 m³ of sand was placed along 2.7 km of beach. A fourth maintenance nourishment occurred in 2002 (February and March) from 150 m north of R180 to 150 m south of R188 when approximately 940,000 m³ of sand was placed along 3 km of beach. A smaller emergency restoration project that used about 350,000 m³ of sand was also constructed in early 2005 to mitigate for sediment losses caused by two hurricanes that affected the project area in September and October of 2004 (H. Frances and H. Jeanne).

2.3.1. Previous Investigations

Studies relevant to the scope of this paper include those by Fernandez (1999), Gravens (1997), Beachler, (1993), and CPE (1994, 1995, 1996, 1998, 1999 and 2001). Salient findings in these studies are described as follows.

Nourishment of Delray Beach affected neighboring beaches due to fill spreading effects. Beachler (1993) described that from 1973 (initial nourishment) to 1990 the fill area lost 1.15 Mm³ of sand when at the same time about 840,000 m³ of sand was deposited on adjacent beaches 3 km to the north and south of the fill area.

Predictions of a one-line shoreline change model were compared with measured shoreline between 1987 and 1992 by Gravens (1997). The coastal segment between R180 and R181 was defined as an EHS by this author. Shoreline change simulations that considered wave transformation over measured nearshore bathymetry (in comparison with an artificially created bathymetry with shore parallel contours) provided better agreement with measured shoreline changes indicating influence of nearshore bathymetry on shoreline changes. As described by Gravens (1997) the EHS near R181 may be related to a gap in the barrier reef system offshore this location. Theoretically, the gap would cause gradients in nearshore wave height that would induce gradients in alongshore transport that could in turn lead to EHS development.

Project performance and development of EHS from 1975 to 1998 and 1975 to 1990 evaluated by Fernandez (1999) using shoreline change simulations compared with the measured shoreline change data. Large deviations between the model predictions and the observed shoreline change

were interpreted as an indication of an EHS (the model could not simulate an unknown natural process). An updrift location near monument R178 was identified as a cold spot (segment that experiences more accretion than predicted), and an EHS was identified at profile monument R187. Finer sand in the south end of the project was suggested as a potential cause for the EHS at R187.

Numerous monitoring reports (CPE, 1994, 1995, 1996, 1998, 1999 and 2001) indicate greater shoreline recession near R186 and R187. In an effort to emphasize the greater magnitude of erosion in this area, CPE (1995) reported that while the mean shoreline retreat of the fill was about 19 m, the area at R187 receded approximately 56 m since construction. Greater erosion at R187 was qualitatively attributed to the extra amount of fill placed and to end losses. Higher rates of erosion near R181 and R183 are reported in 1995 and 1995 but discontinued in subsequent years (CPE, 1994, 1995, 1996, 1998, 1999, and 2000). Segments 500 m up and downdrift of the nourishment area accreted slightly during most of the monitored period.

2.4. MEASURED SHORELINE AND VOLUME CHANGES AFTER THE 1992 NOURISHMENT PROJECT

Computations of shoreline and volume changes following the 1992 nourishment were based on data from annual beach profile surveys (for monument locations see Figure 2.2). The shoreline was defined as the 0.52 m contour NGVD which corresponds to the mean water level at Delray Beach. Volume changes were calculated from the monument location (generally on the back of the dune) to the -7.5 m depth contour which is the offshore limit of most surveys and the estimated closure depth of the study area (CPE, 2001). Shoreline positions in December 1992, post construction survey, and June 2001 were overlaid on top of geo-rectified aerial photography (obtained in March 2001) in a GIS framework (Figure 2.2). This facilitates the visualization and interpretation of shoreline change patterns and their association with beach and dune geomorphology. Because of the clarity of Florida waters, surf zone morphology can be easily mapped and interpreted from aerial photographs (*e.g.* Benedet, 2002; Finkl and Warner, 2005).

Deviations between post-construction shorelines and the 2001 shoreline (Figure 2.2) increase on the downdrift segment of the fill (between monuments R186 and R187) indicating more erosion than on other fill segments. Crescentic bars, which are the most persistent type of bar morphology observed at the project area, have horns between bars not attached to the beach near the downdrift end of the fill whereas the on the other areas irregularly spaced crescentic bars with horns attached to the beach occur, suggesting a morphodynamic relationship between erosion rates and surfzone morphology. Shoreline and volume change from the post-construction survey (December 1992) to the last survey (June 2001) reached -80 m between R186 and R187, about -40 m between R184 and R185, and about -60 m at R183 (Figure 2.3). The updrift beach segment (R175 to R180) showed an average accretion of 11 m while the downdrift beach (R189 to R191) accreted about 6 m during the eight and a half years evaluated (Figure 2.3).

Volume changes to the -7.5 m depth contour (offshore limit of the profile surveys) between 1992 and 2001 shows a similar general trend to the shoreline changes (Figure 2.3). Total volumetric changes were estimated by multiplying the unit volume change by the distance between profile monuments. Between 1992 and 2001, a cumulative volume of about 448,000 m³ was lost from the fill limits, of this volume, 177,000 m³ (about 40%) eroded from the beach segment between profile monuments R186 and R187.



Figure 2.2. Shoreline positions overlaid on georectified aerial photography obtained in 2001. The 1992 shorelines shown were surveyed immediately after construction of the 1992 nourishment project (Dec, 1992) and June 2001 is the last complete survey of the project area prior to the construction of the fourth consecutive nourishment project in April 2002.

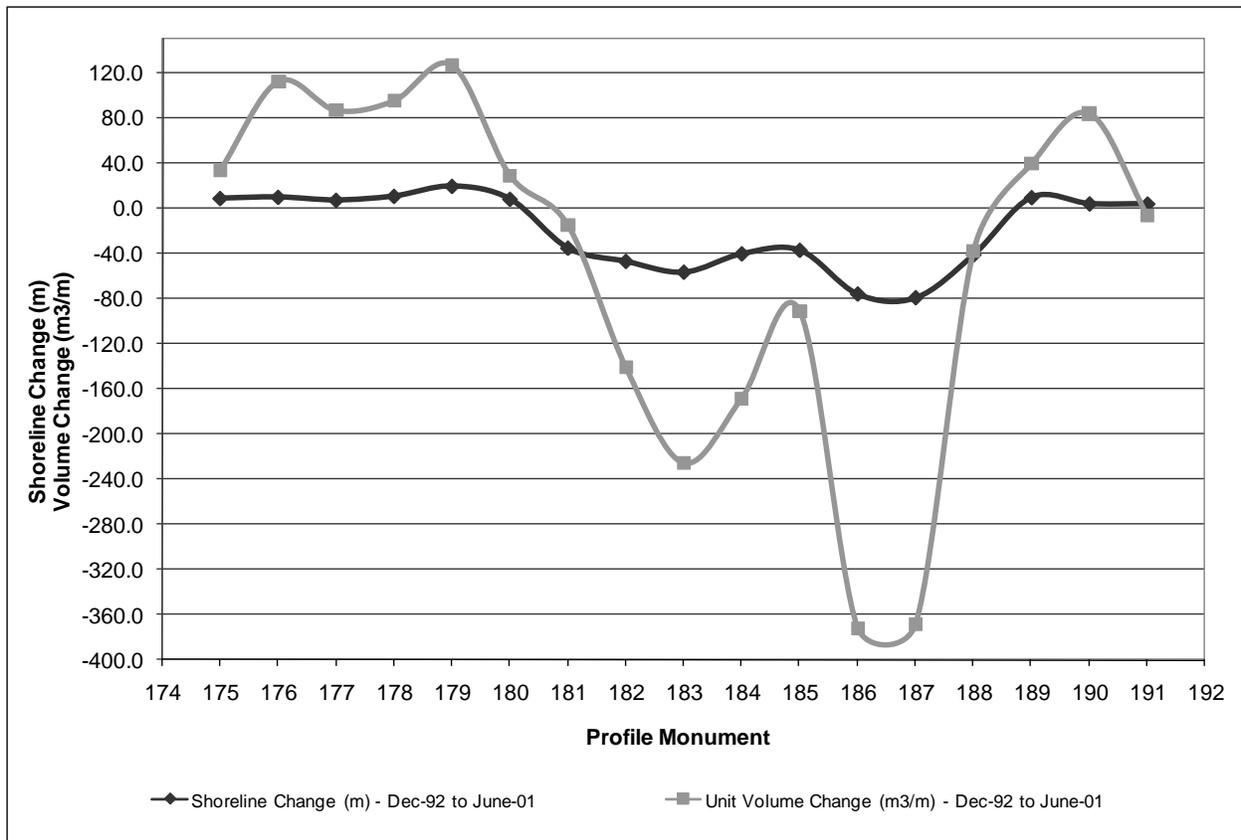


Figure 2.3. Shoreline changes (m) and volume changes (m^3m^{-1}) from the post-construction survey (December 1992) to the last survey of the entire study area (June 2001).

2.4.1. Annual Variability of Beach Fill

Annual shoreline and volume change rates vary greatly along the study area. Although up- and downdrift shorelines were slightly accretion for most of the time period evaluated (1992-2001) (Figures 2.4 and 2.5), these segments eroded, however, in 1993-1994 and 1999-2000. The nourishment area eroded for most of the monitored period but accretion was exceptionally observed between 1995-1997, 1997-1998, and 2000-2001. Periods of accretion positively correlated with mild wave conditions (*i.e.* Hartog, 2006). Most of the shoreline and volume change occurred during the first two years post-construction (Figures 2.4 and 2.5) and from 1999 to 2000 when three tropical storms impacted the study area. Relative high shoreline retreat and volume losses observed during the first two years post-construction strongly influenced the shape of the shoreline and volume change curves for the entire study period.

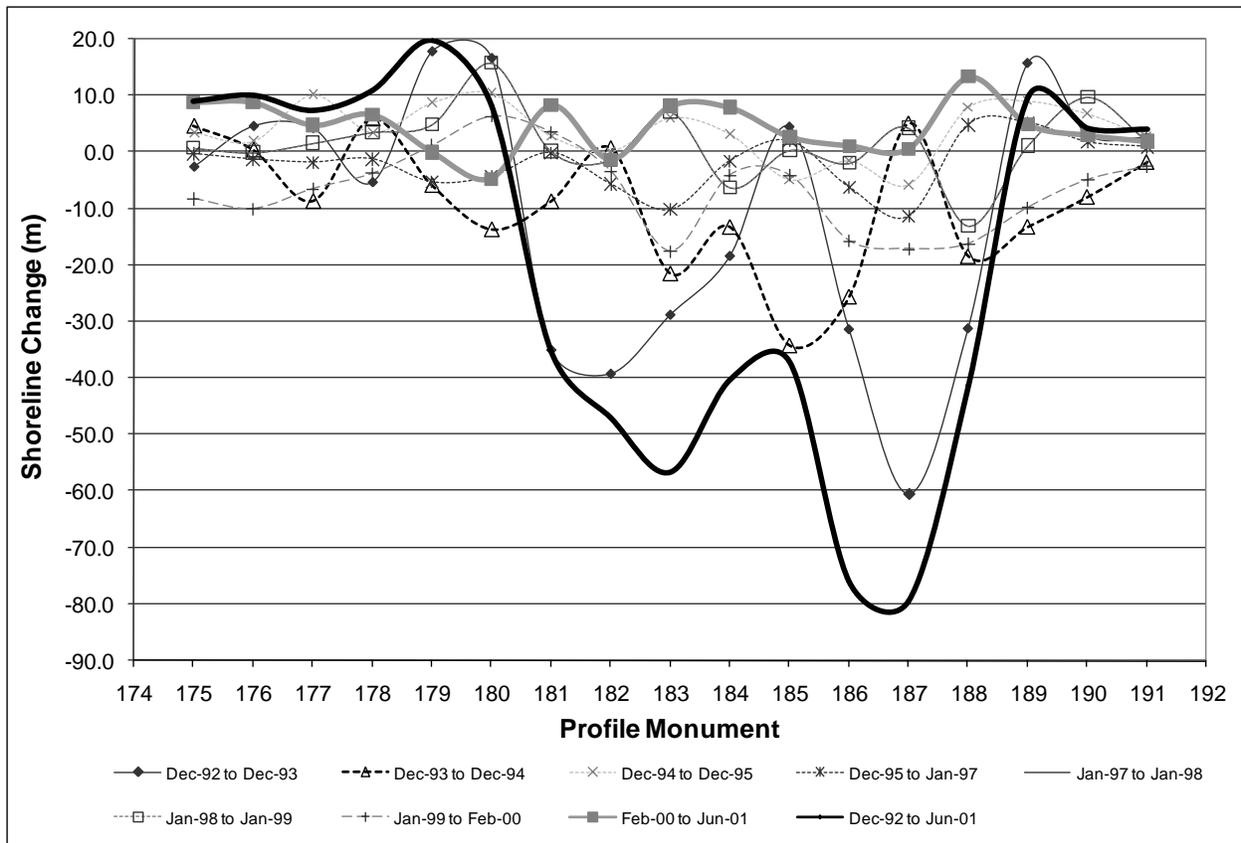


Figure 2.4. Shoreline Changes calculated between annual survey intervals for the Delray Beach project area contrasted with the total changes from December 1992 to January 2001 (thicker black line).

Monuments that eroded relatively more than the rest of the fill, visualized in Figures 4 and 5, include R183, R186 and R187. The shoreline on R186 and R187 retreated almost every year except for two periods (1993-1994 and 1998-1999) (Figure 2.4). Greater shoreline retreat also occurred near R183 for most of the time except for 1993-1994, 1998-1999 and 2000-2001 where accretion occurred (Figure 2.4).

Volume losses of R183, R186 and R187 were also greater than the rest of the project for most years but for two (January 1997 to January 1998 and January 1998 to January 1999) when accretion occurred on these locations. Relatively small volume gains were observed in the up- and downdrift segments throughout most of the monitoring period simultaneous to erosion of the beach fill indicating some alongshore spreading of fill sediments. Further analysis of beach profiles shows that accretion of about $200 \text{ m}^3 \text{ m}^{-1}$ observed at profile R181 between 2000-2001 period (see Figure 2.5) was mostly due to sedimentation in the inner and outer bar systems, thus although a large volumetric gain occurred, very little shoreline change was observed in this area during the same time-period (see Figure 2.4).

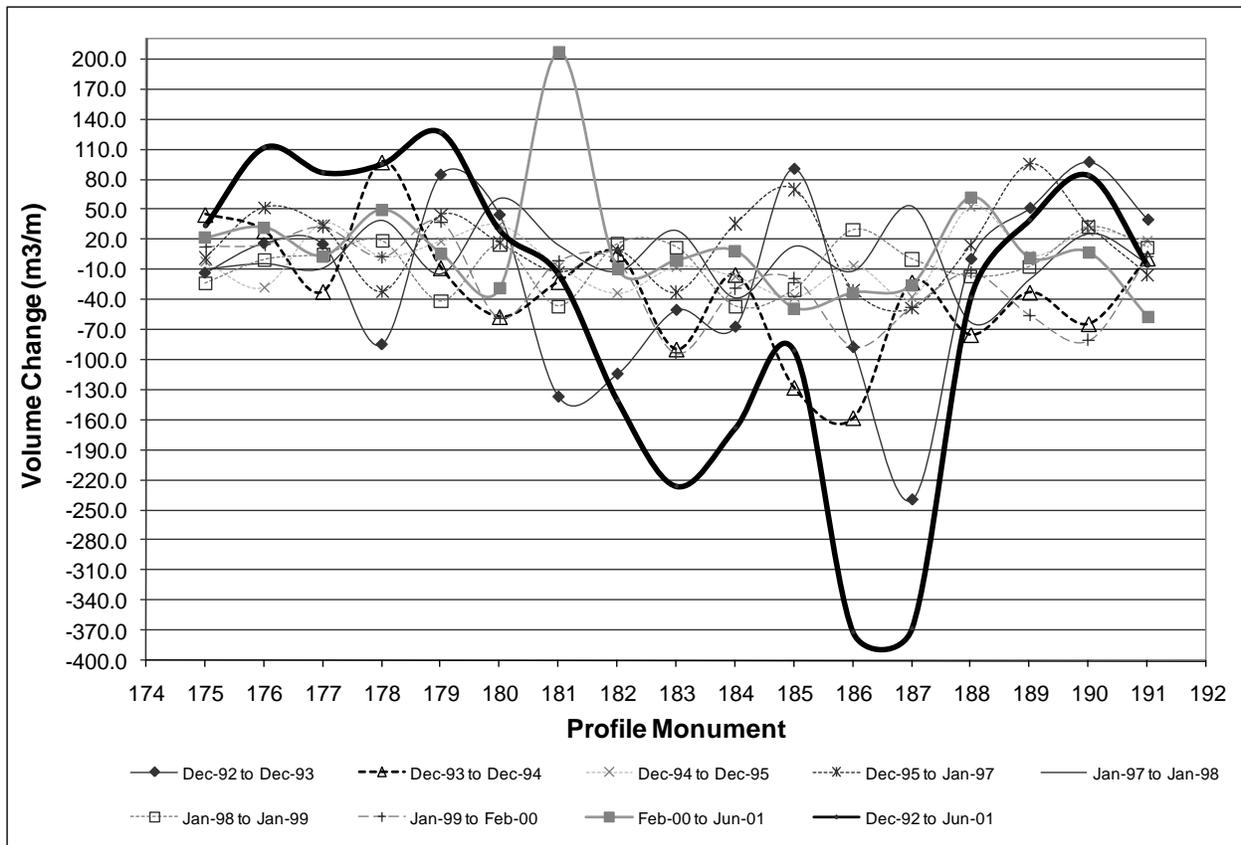


Figure 2.5. Volume changes per unit length of beach m^3m^{-1} calculated between annual survey intervals for the Delray Beach project area contrasted with the total changes from December 1992 to January 2001 (thicker black line).

2.4.2. Identification and Parameterization of Erosional Hot Spots (EHS)

EHS have been investigated by a number of authors in the past. Kraus and Galgano (2001), for example, defined an EHS as “an area that experiences sediment transport potential without having adequate sediment supply erodes more rapidly than the adjacent beaches or more rapidly than anticipated during design and can be quantified and qualified by several metrics. Examples are loss of beach width, loss of sediment volume and percentage of fill remaining of the amount placed.

The EHS definition adopted in this manuscript was adapted from the one provide by Kraus and Galgano (2001), specifically to define EHS occurring within a nourishment project. An EHS was defined here as: “An erosional hot spot is an area within a beach nourishment project that erodes at least two times more than the nourishment average and can be quantified comparing the volume loss (m^3m^{-1}) or shoreline retreat (myr^{-1}) of a specific beach segment with the average volume loss of the entire nourished area”. If the hot spot is quantified based on volume losses (m^3m^{-1}) over the entire beach profile (from the toe of the dune to the closure depth) it is caused by alongshore processes (cross-shore transport is conserved within the active profile), however if shoreline change data (myr^{-1}) is used, the hot spot may be caused by either alongshore processes or cross-shore adjustments (*i.e.* persistent erosion of subaerial beach and deposition in the surf zone).

Several parameters have been historically used to quantify EHS viz. historical shoreline and volume changes (Liotta, 1999), percentage of fill remaining in a specific beach segment vs. the

entire fill area (STAUBLE, 1994), comparison of erosion rates of specified beach segments with background rates or average rate of fill erosion (Finkl and Kerwin, 1997), and comparison of one-line model predictions with shoreline change measurements (Gravens, 1997; Fernandez, 1999).

In this paper, EHS are defined by comparing volume change per unit of beach length, hereinafter referred to as ‘unit volume change’ (m^3m^{-1}), at each monument profile, with the average unit volume change of the entire fill. Unit volume loss at each monument profile (m^3m^{-1}) compared with the average unit volume loss for the entire fill over the entire period monitored is shown in Table 2.2. Monuments that eroded at least two times (100%) more than the nourishment average were classified as EHS. From Table 2.2 it seems that unit volume loss at monument R183 was about 46% greater than the nourishment average and about 9% larger at monument R184. Unit volume losses from monuments R186 and R187 were 141% and 139% greater than the nourishment average during the entire monitoring period (Table 2.2). Based on Table 2.2, the area between profiles R186 and R187 are classified as EHS. Monuments R184 and R183 tend to erode more than the nourishment average but are not classified as an EHS according to the definition of EHS adopted here.

Some EHS only develop during adjustment of the artificially placed fill (*i.e.* initial two years after nourishment) due to lateral spreading of over-filled areas (erosion of a locally advanced shoreline). On the other hand, EHS areas may persist as a response to recurring physical processes. In order to differentiate persistent EHS from areas that may have eroded faster than the nourishment average only during the initial adjustment years, volume change rates during the two initial years after construction (where most of the adjustment occurred) were removed from the dataset for further analysis.

Table 2.2. Volume changes from December 1992 (post construction) to June 2001 for each profile monument compared to the average volume change rate for the entire nourished area. Monuments that eroded at least twice (more than 100% extra erosion) more than the fill average are marked in bold.

Beach profile monument	Volume change per beach profile monument ($\text{m}^3\text{m}^{-1}\text{yr}$)	Average volume change for the entire nourishment ($\text{m}^3\text{m}^{-1}\text{yr}$)	Anomaly (difference between monument and nourishment average)	Percent (%) of extra erosion (over fill average background)
R180	3	-17	20	118
R181	-1	-17	17	96
R182	-17	-17	0	-1
T183	-29	-17	-12	-70
R184	-20	-17	-3	-16
R185	-11	-17	6	35
R186	-49	-17	-31	-184
T187	-45	-17	-27	-160
R188	-5	-17	12	70

Volume changes for each monument profile compared with average volume change for the entire nourished area from 1995 (three years post-construction) to June 2001 are shown in Table 3. When the two adjustment years are removed from the record, the average fill-volume change decreases from $-154 \text{ m}^3\text{m}^{-1}$ (Table 2.2) to $-20 \text{ m}^3\text{m}^{-1}$ (Table 2.3). Between December 1995 and June 2001 monument R183 lost about 297% more volume than the average rate of fill erosion and R184 lost 235%. Monuments R186 and R187, earlier classified as an EHS based on Table 2, lost respectively 487% and 224% more volume than the nourishment average (Table 2.3). According to these results, from 1995 to 2001 there were two areas with higher erosion rates within the fill, one between monuments R183 and R184 and another between R186 and R187. Monument profile R186 was also the only segment where beach width was narrower than the design width at the end of the project lifetime (CPE, 2000), which is also one of the recommended parameters to define hot spots according to the definition of Kraus and Galgano (2001). Because the EHS signal was stronger and occurred during and after fill adjustment between profile monuments R186 and R187 (Tables 2.2 and 2.3), further analysis of potential mechanisms presented hereinafter will focus on this beach segment.

Table 2.3. Volume changes from December 1995 (three years post construction) to June 2001 for each profile monument compared to the average volume change rate for the entire nourished area. Monuments that eroded at least 100% more than the fill average are marked in bold.

Beach profile monument	Volume change per beach profile monument ($\text{m}^3\text{m}^{-1}\text{yr}$)	Average volume change for the entire nourished area ($\text{m}^3\text{m}^{-1}\text{yr}$)	Difference between monument and nourishment	Percent (%) of extra erosion (over background or fill average)
R180	7	-4	11	265
R181	26	-4	30	718
R182	-5	-4	-1	-28
T183	-15	-4	-11	-261
R184	-14	-4	-10	-231
R185	-8	-4	-4	-99
R186	-23	-4	-19	-443
T187	-17	-4	-13	-316
R188	7	-4	11	256

2.5. POTENTIAL MECHANISMS FOR THE EHS ON THE SOUTH END OF THE FILL

Possible causes for localized higher sediment volume losses at R186 and R187 are evaluated in the following sections of this paper using monitoring data, and preliminary numerical modeling of waves and currents.

2.5.1. Alongshore Grain Size Distribution

Alongshore variations of grain size have been suggested as a potential cause for differential rates of fill erosion where finer-grained sediments are associated with EHS and coarser-grained sediments are associated with slower erosion rates (Fernandez, 1999).

Grain size information in various years, available from annual monitoring reports (CPE, 1994, 1995, 1996, 1998, 1999 and 2001), was evaluated to investigate alongshore grain size variations within the nourished area during the studied period. Samples were collected from the toe of the dune to an offshore depth of about -7.5 m at profile monuments R177, R181, R184 and R187. Cross-shore samples were averaged for each monument location to obtain a profile mean or 'composite' grain size. Although variability in grain size in the cross-shore direction occurs, as discussed by Benedet *et al.* (2004), this approach was adopted to perform a comparative analysis of alongshore patterns of distribution in beach grain sizes. A plot of mean grain sizes from 1992 to 2000 (Figure 2.6) shows that the mean grain size at R184 and R187, which were areas with higher erosion, was similar to grain sizes at other beach locations (R177 and R181) during most of the monitored years. Beach sediments at monuments R184 and R187 were finer than beach sediments at monuments located further to the north (R177, R181) during the first post construction survey conducted February 1992 (Figure 2.6), however, about 10 months later, (December, 1993) the grain size difference between R177 and R187 was minimal, 0.28 mm versus 0.25 respectively and the grain size at R184 is coarser than anywhere else in the beach (0.33 mm) indicating rapid mixing of fill sediments with pre-existing sediments. The absence of large alongshore variations in beach grain size that are persistent in time within the beach fill area indicate that grain size distribution is not a major parameter controlling EHS development since the higher erosion in the EHS segment occurs throughout the monitoring period.

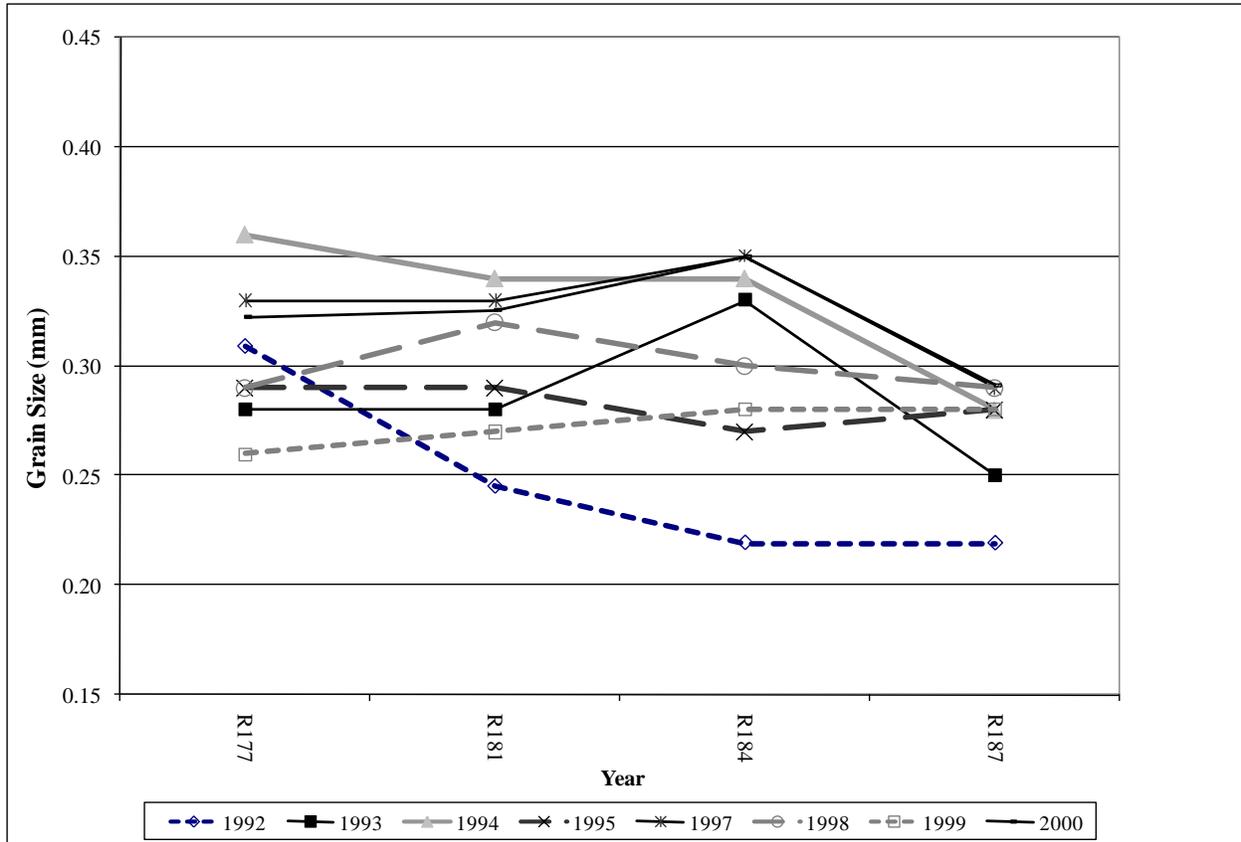


Figure 2.6. Alongshore distribution of grain size along the project area at selected profile monuments surveyed on an annual basis.

2.5.2. Effects of Shore-Parallel Reefs and Borrows

Nearshore rock outcrops, coral and rock reefs, gaps between shore-parallel barrier reefs, and sand borrows along the southeast Florida coast may affect nearshore wave heights and influence currents and sediment transport patterns that in turn would impact adjacent beach fills (Gravens, 1997; Finkl *et al.*, 2005). An EHS observed near R180 and R181 between January 1997 and October 1992 could be related to a reef gap offshore as suggested by Gravens (1997). In a numerical wave modeling exercise Finkl *et al.* (2005) reported large alongshore variability of nearshore wave heights along the Delray Beach fill area and attributed this variability to offshore geomorphic features such as reef shape, reef gaps and presence of borrow pits. The shore-parallel barrier reefs occur in -15 to -20 m water depths whereas borrow areas are located in shallower waters (-10 to -15 m). The borrow pits were excavated 2 to 15 m below the seabed surface, with older borrows (dredged in 1973 and 1978) being deeper than recent borrows (dredged in 1992 and 2002).

To further evaluate the influence of the seafloor morphology (borrow areas and barrier reefs) on nearshore wave propagation, numerical wave modeling was conducted using a spectral wave model (SWAN) with original bathymetry (surveyed October 2002) and with artificially created bathymetries where the barrier reef gaps and borrows were removed mathematically by linear interpolation. Borrow depressions were leveled with adjacent areas and reef elevations were removed by interpolating basal elevations of the reef both seaward and landward. Although

simulations were conducted for several wave conditions, only results for the most severe and persistent waves (NE storm waves) are shown here.

Figure 2.7 shows SWAN simulations for NE waves (60 degree angle of approach) with H_o of 2 m and T_p of 11.5 seconds with three different bathymetry scenarios. Because these are swell waves, a narrow wave energy distribution of 5° was used. The numerical simulations included wave transformation over bottom irregularities (refraction) and wave energy dissipation due to breaking and bottom friction. Although effects of reflection from borrow side-walls may be relevant in specific cases (*i.e.* in shallower borrows with steeper side walls as per Michaelsen *et al.*, 2005; Bender and Dean, 2003) they were not included in the calculations shown herein. Diffraction effects which may also be relevant in reducing alongshore wave height gradients were not included in these preliminary calculations. Detailed description of model settings and physical parameters adopted is available in Hartog (2006).

Up to 1 m alongshore variability in wave height (50% of the input boundary wave condition) are observed in the simulation that used original bathymetry (see left plot on Figure 2.7). When the offshore shore parallel barrier-coral reefs are removed (artificially created bathymetry) a pattern of alongshore variability in wave heights, similar to the simulation with the original 2002 bathymetry, is observed (see middle plot on Figure 2.7). When the borrow pits are removed the alongshore variability in wave heights are smoothed out and the most prominent wave shadow and wave focusing zones disappear (see right plot on Figure 2.7 compared to middle and left plot).

For quantitative analysis wave heights along a shore parallel grid line located about 600 m offshore were evaluated using the results shown in Figure 2.7. This analysis indicated that the offshore barrier-coral reefs slightly reduce nearshore wave heights at wave focusing locations and is generally less than 10% of the boundary wave height (10-20 cm). Compared to the effects produced by the borrow areas, the effects of the shore parallel barrier-coral reefs are minor along the study area. Significant gradients in nearshore wave height do not seem to be directly linked to the development of the hot spot on the south end of the project (between R186 and R187), because the location of the major wave focusing and wave shadow zones do not coincide with this hot spot location. The other erosional area (R183 to R184), however, is associated with high variability in alongshore wave height induced by irregularities in offshore bathymetry. These simulations are preliminary and provide initial lines of evidences into the processes causing the EHS, however, further modeling analysis including evaluation of wave-induced alongshore flows and sediment transport is needed.

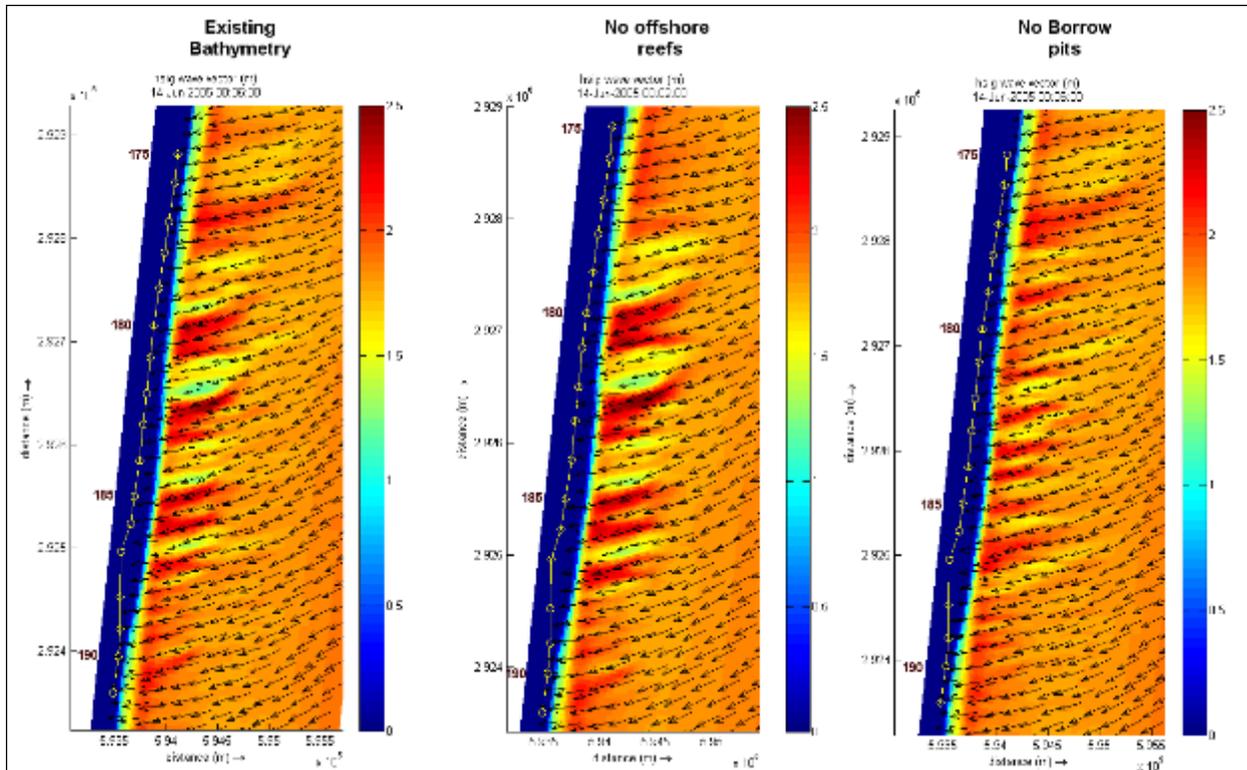


Figure 2.7. Results from SWAN simulations for NE waves (60 degrees angle of approach) with H_o of 2 m and T_p of 11.5 seconds and 50 wave energy distribution. The left plot was conducted with existing post-construction bathymetry, the offshore shore parallel reef were removed in the middle plot while the offshore borrows are removed in the right plot. Alongshore patterns in wave height are similar between the left plot (existing condition) and the middle plot (reefs removed). Once the borrow pits are removed (right plot) the alongshore variability in wave heights are smoothed out as the most prominent wave shadow and wave focusing zones disappear. Variations in wave height are, however, relatively small in the hot spot area (R186 and R187).

2.5.3. Fill Residual Bathymetry and Planform (Shoreline Orientation)

The shoreline orientation and morphology induced by the beach fill may also be partially responsible for EHS development on the downdrift end of the fill. The areas with the highest erosion rates are also the areas that received the larger amount of fill originally (Figure 2.8) (CPE, 1994, 1999, 1996, 2001) suggesting that post-nourishment template distribution affected overall sediment redistribution patterns and fill erosion rates. Figure 2.8 shows that locations where higher erosion rates were observed (profile monuments R186 and R187) received the significantly higher amounts of fill. During the initial years post construction it is thus expected that erosion of a locally advanced segment of the shoreline (lateral spreading) occurred in this area causing the higher erosion rates observed. Two years after construction, however, fill distribution is relatively homogeneous but the two profile monuments in the end of the fill continued to erode at faster rates than the rest of the fill.

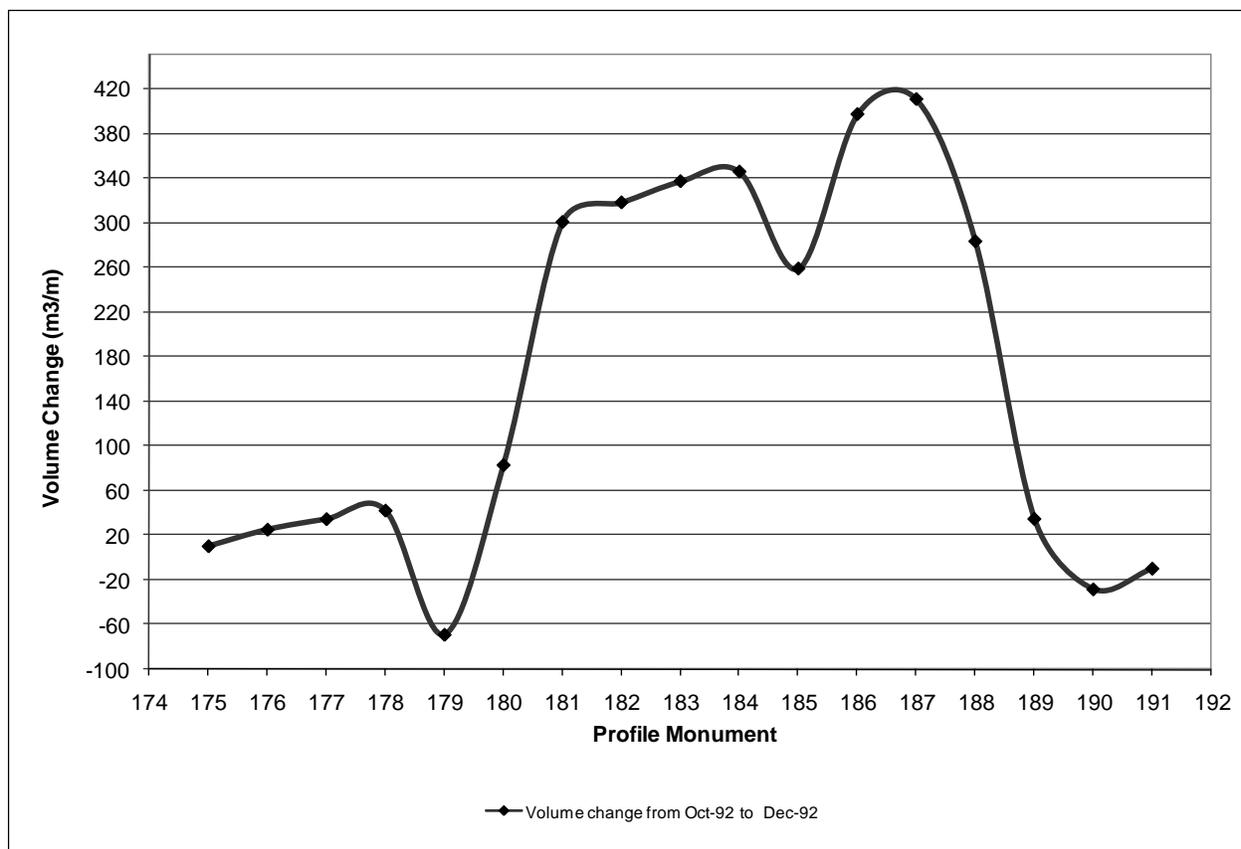


Figure 2.8. Volume changes from October 1992 (pre-construction survey) to December 1992 (post construction survey) showing distribution of fill sands. The nourishment is delimited between monument profiles R180 to R188, higher volumes were placed in the south end of the fill (profile monuments R186 and R187) to counteract higher erosion rates observed in this area after the previous fills.

The planform of an eroded beach is modified by introduction of sediments into the beach system via beach nourishment. Modification of shoreline orientation on the downdrift end of a nourishment increases wave obliquity that in turn leads to an increase in alongshore current velocity in the transition zone between the nourished and the non-nourished downdrift beach. Volume losses at the end of nourishment projects, referred to as end losses, are common along open coast nourishments (*e.g.* Dean, 2002). Fernandez (1999) indicated that the losses on the downdrift end of the Delray nourishment were higher than predictions of beach nourishment diffusion estimates. Waves from the northeast are predominant at Delray Beach (*e.g.* FINKL, 1994, Fernandez, 1999, Benedet *et al.* 2002) and thus responsible for most alongshore sediment transport. The Delray Beach shoreline is generally oriented in N-S direction (around 6° east of north), but the shoreline near the downdrift end of the nourishment (EHS segment) assumes an NE-SW orientation of 10° to 15° (Figures 2.1 and 2.2) associated with fill-induced beach planform modification. Because of the orientation of the shoreline at the downdrift end of the fill, wave rays from the northeast are more shore-parallel in this zone thus alongshore current velocity (and sediment transport) in this region will increase because those are largely dependent on angle between the incident waves and bottom contours (*e.g.* Longuet-Higgins, 1970).

To evaluate the effect of beach planform configuration (shoreline orientation) on the alongshore current velocities, a simulation with a hydrodynamic model (DELFT 3D) in 2DH mode

was conducted. The model calculated depth-averaged current velocities along the nourished area during northeastern wave conditions (Figure 2.9). The hydrodynamic model was forced by the output from a spectral wave model (SWAN). The SWAN simulation was conducted for a NE wave event with 2 m waves, 11.5 s T_p and 60° approach with 5° energy width distribution. A harmonic function to represent tides, and a representative wind condition were also included. Lateral boundary conditions were set up as water level gradients, as described by Roelvink and Walstra (2004). The flow calculation grid was nested in a coarser wave grid that provided wave boundary conditions for flow computations. The input bathymetry for the refined flow grid was created from a dense airborne laser bathymetry (ALB) dataset (*e.g.* Finkl, 2004). The ALB survey was conducted about six months after the completion of the 2002 nourishment which was dimensionally similar to the 1992 nourishment. Detailed description of model settings and physical parameters adopted are given by Hartog (2006).

Simulation results show that current velocities at the surf zone are higher near the end of the fill where they reach about 1.6 ms^{-1} compared to currents generally less than 1 ms^{-1} throughout the rest of the study area (Figure 2.9). Smaller areas with stronger current velocities (1.0 to 1.4 ms^{-1}) are observed within the nourished area (near R182 and R184, Figure 9), due to combined effects of approaching wave angle and gradients in wave height induced by nearshore features (sand borrows). Alongshore current velocities of similar magnitude (1.5 ms^{-1}) were measured by RENIERS *et al.* (2002) at Duck, NC during the Delilah experiment, under similar wave conditions, corroborating velocity simulation results reported here. Figure 2.9 shows that, in addition to nearshore bathymetric features, post-construction beach orientation and bathymetry can influence the hydrodynamics of the nourished area and consequently influence beach nourishment performance.

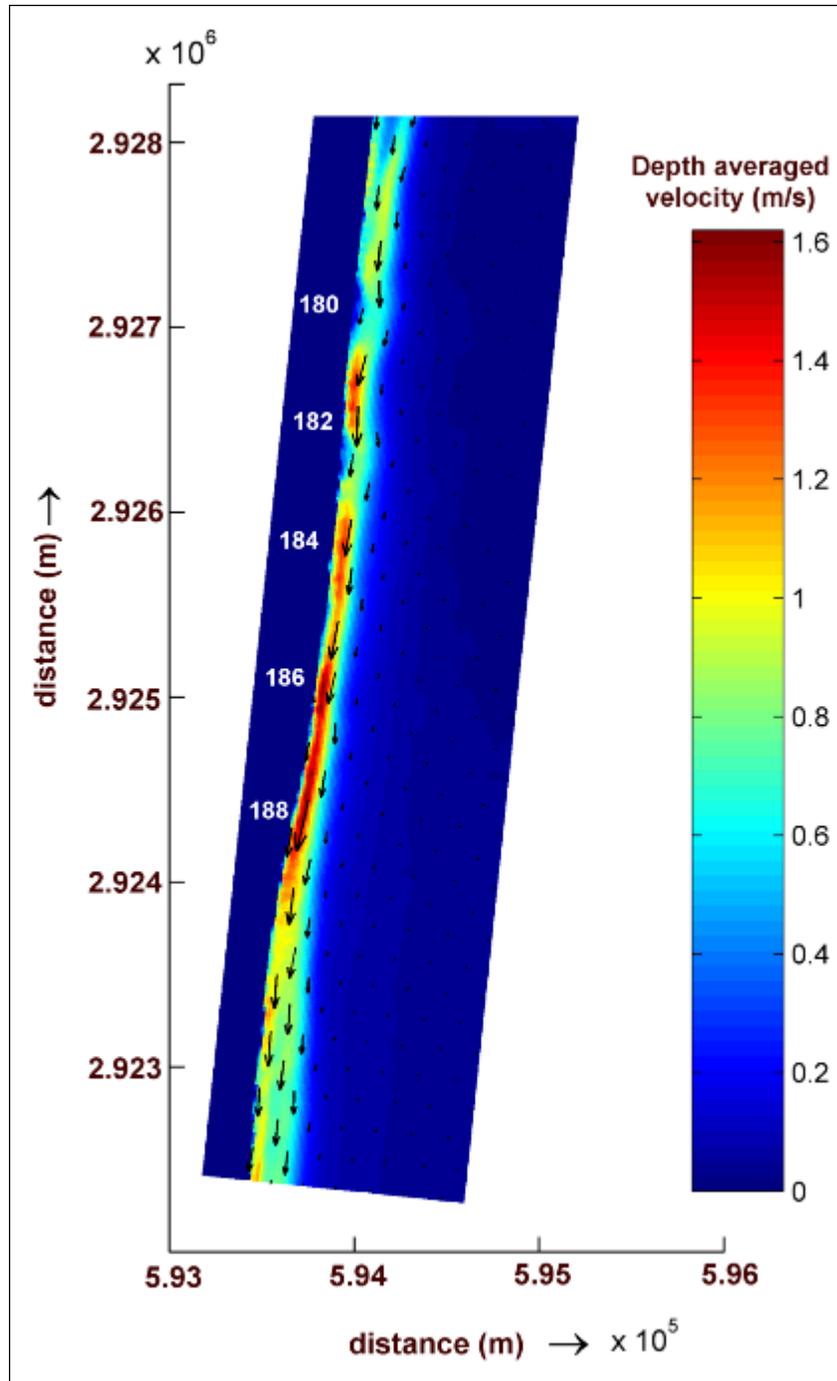


Figure 2.9. Results from current simulations during a strong NE wave event (2 m H_s , 11.5 s T_p and 60° approach). The hydrodynamic model was forced by the output from a spectral wave model. Tides, and a representative wind condition were also included. The input bathymetric grid was obtained about 67 months after the 2002 nourishment project (which had similar dimensions than the 1992 nourishment project). Note that current velocities are higher near the end of the fill where they reach about 1.6 m/s when compared to currents of generally less than 1 m/s throughout the rest of the study area.

2.6. DISCUSSION

2.6.1. Fill Erosion Rates and Identification of EHS

EHS areas were identified comparing erosion rates of individual beach profile monuments with the average erosion rate of the beach nourishment. The area between monuments R186 and R187 is an EHS during both time periods evaluated (1992-2001 and 1995-2001; Tables 2 and 3) while R183 and R184 may be classified as an EHS for the second time period evaluated (1995 to 2001; Table 3). Because the EHS signal was stronger for monuments R186 and R187 (see Tables 2 and 3) further analysis of potential mechanisms focused on this beach segment. A hot spot near R181 as described by GRAVENS (1997) was not observed in the data analyzed here. It is possible that higher erosion near monument R181 observed by GRAVENS (1997) was not observed during the time period evaluated herein because of modifications to morphodynamics of this area associated with a new beach configuration created by the 1992 nourishment project, dredging of recent sand borrow areas or variability in wave activity.

Comparison of volume changes at individual beach segments with the average volume changes of the entire beach fill may be used to define EHS within a beach nourishment project elsewhere. Special attention must be dedicated, however, to the influence of fill adjustment on hot spot identification, a hot spot may be persistent in time, or may be due to erosion of a locally advanced shoreline during initial fill adjustment years. The statistical meaning of the “fill average volume change” is vulnerable to the number of sampling stations, as many sampling points (monument locations) available, more reliability the average measure will have.

2.6.2. EHS Controlling Mechanisms

Grain sizes at accreting sections of the study area (*i.e.* R177) are not persistently coarser than the rest of the project, and the grains in the areas with higher erosion *i.e.* R184 and R187 are not persistently finer than the rest of the project suggesting that alongshore distribution in sediment grain size is not controlling EHS development. Grain sizes in Delray Beach also vary largely in a cross-shore direction (*i.e.* BENEDET et al., 2004) so small differences in grain size could be due to sample spatial location (*i.e.* samples just a few meters seaward or landward) or temporal variability of beach grain sizes due to energy regime (*e.g.* King, 1959).

Wave model analysis showed that although large variability in nearshore wave heights occur the wave focusing and wave shadow zones do not coincide directly with the EHS in the south end of the project (between R186 and R187). Additional wave modeling analysis conducted by HARTOG (2006) with 14 different wave conditions confirms this finding. The question remains, however, whether gradients in wave height at the neighboring areas cause flow and sediment transport gradients that indirectly affect erosion at the EHS segment. There is a direct geographic correlation between fluctuations in alongshore wave height and associated fluctuations in current velocity with the highly erosional beach segment between R183 and R184.

Because the EHS was identified on the basis of volume changes of the entire active beach profile (from the toe of the dune to the approximate closure depth), and analysis of beach profiles showed that the profiles closed well at the seaward limits of the surveys (no significant volume

losses by cross-shore processes beyond the beach profile survey limits) it is assumed that the EHS is caused by alongshore transport processes.

Alongshore current accelerations are observed on the south end of the project (EHS segment between R186 and R187). Increased current velocities in this area are attributed to fill-induced changes shoreline orientation and to a lesser degree wave height variations induced by offshore morphology. These flow accelerations may cause and increased sediment transport potential leading to the higher erosion rates observed in this beach segment.

If flow accelerations due to fill planform shape (the shoreline orientation is about 6° N-S throughout most of the fill and 10° - 15° NE-SW in the south end of the fill prior to adjustment) is the cause of erosion in the south end of the project, this processes would generally be expected to decrease with time, as the nourishment planform adjusts to smoother curvature and the project increases in length (eroded sediments from the project area deposit in adjacent shorelines). Although volumetric losses from the EHS area are significantly higher during the first two years post-construction due alongshore adjustments of a locally advanced shoreline segment, higher than average erosion rates persist in the south end of the fill even after the fill adjustment years (Table 3) suggesting that some other mechanism, not clear at this moment, is also affecting erosion rates at the EHS segment.

2.7. CONCLUSIONS

Alongshore variability on the morphodynamic response of a nourished beach was evaluated here and hypothesis to explain the development of one EHS in the downdrift end of a beach nourishment were evaluated. Delray Beach was nourishment in December 1992 about 914,000 m³ of sand was placed along 2.7 km of beach. In 2001, eight and a half years after construction, 448,000 m³ of fill sediments were lost from the nourished area. Since volume changes were calculated to the approximate closure depth of the project area it can be assumed that volume losses are attributed alongshore processes such as fill lateral spreading and gradient in alongshore sediment transport. Most of the volume loss occurred in the first two years after the nourishment as the fill adjusted in planform. Large annual variability in fill erosion rates was also observed. During years where wave conditions were mild the project remained stable or showed slight accretion while in 1999, an extremely active year in terms of tropical and extra-tropical storms, high volume losses were observed.

Two zones with higher erosion were identified and classified as erosion hot spot (EHS). Volume losses at one EHS occurring in the south end of the fill were at least 100% more than the average volume loss of the nourished area during and after beach nourishment adjustment. About 40% of the total volume loss accrued from this from 600 m long EHS, in a project that is 2.7 km long.

Potential mechanisms to explain the EHS development in the south end of the fill were evaluated including the influence of nearshore features (barrier coral reefs, reef gaps and borrow pits) on nearshore wave propagation, alongshore grain size distribution patterns and beach nourishment planform – shoreline orientation.

Evidence analyzed here suggests that gaps in the offshore barrier reef system did not cause the EHS, in fact the effects of the barrier reefs on the nearshore waves are relatively minor. Alongshore variability in wave height and associated wave shadow and focusing zones observed along the northern and central part of the nourishment were due to wave transformation over the dredged borrows. Near the EHS on south end of the project (between R186 and R187), however, variations in nearshore wave heights were relatively small compared to other segments of the project.

Grain size differences alongshore were not the cause of increased erosion of EHS segments since grain sizes are not persistently finer where higher erosion is observed or vice-versa. Grain size distribution trends within the project area vary significantly temporally and spatially and grain size differences within the project area can be considered minor.

Alongshore currents are stronger in the downdrift end of the project on the EHS segment where the highest volumetric losses are observed. This localized increase in current velocity is likely caused by changes in shoreline orientation induced by the beach nourishment. The preliminary analysis and numerical modeling carried out indicates that changes in shoreline orientation induced by beach nourishment plays a significant role in the strong rates of erosion observed at the erosional hot spot situated in the terminal end of the beach nourishment, especially during the first two years post construction where fill alongshore adjustment is taking place. However, the persistency of high erosion rates at the same beach segment, during the entire beach nourishment lifetime suggests that other processes are at play, possibly alongshore gradients in hydrodynamics induced by offshore borrow areas.

The relative effects of these morphological features (shoreline angle and borrow areas) on the increased current velocities observed on the Erosional Hot spot segment should be further investigated by integrated simulations of waves, flows, sediment transport and beach morphology changes.

Regardless of the cause, similar phenomena (increased current velocities in the downdrift end of beach fills) may be able to explain higher than expected end losses in other open-coast fills where a strong net alongshore current is observed. Bathymetric modifications such as selective dredging or submerged structures aimed at reducing wave obliquity at the downdrift end may be able to reduce volume losses on this highly erosional area (downdrift end of the fill) and could be used to reduce long-term volumetric requirements of such projects.

ACKNOWLEDGEMENTS

For reviewing this manuscript and providing helpful suggestions, the authors thank Marcel Stive (Delft University of Technology, The Netherlands), Robert Dean (University of Florida, Gainesville, Florida, USA), Antonio Klein (UNIVALI, Itajai, Santa Catarina, Brazil), and Dieter Muehe (UFRJ, Rio De Janeiro, Brazil). We also thank colleagues at WL Delft Hydraulics (Mark van Koningsveld, Dirk-Jan Walstra, Edwin Elias) for helping through development of this work.

CHAPTER 3. INVESTIGATION OF THE PHYSICAL MECHANISMS THAT INFLUENCE THE PERFORMANCE OF THE DELRAY BEACH NOURISHMENT PROJECT UTILIZING SENSITIVITY ANALYSIS WITH DELFT3D

Abstract

Delray Beach, an open coast beach located on the southeast coast of Florida, U.S., has been periodically nourished since 1973. The morphological evolution of these nourishments has been influenced by design aspects (e.g. changes in shoreline orientation), extreme events (hurricanes, northeastern storms) and dredging of offshore borrow areas dredged to provide sand for the nourishment project. This paper describes an analysis of the physical processes influencing nourishment performance using the process-based model Delft3D. The analysis distinguishes three main steps: (1) a wave, (2) a hydrodynamic and (3) a cursory morphological modeling analysis. The wave analysis shows that the oldest, deeper, borrow pits (dredged in 1973 and 1978) have the largest effect on the nearshore wave climate, while the effects of the reefs can be considered negligible. Results from the hydrodynamic analysis indicate that differences in wave height cause variations in alongshore current velocities related to differences in wave set-up and local wave angle. The morphologic analysis also shows a large influence of the older borrows on fill performance. Some accretion behind the dredge pits near the offshore bar is predicted by the model, however this feature couldn't be confirmed with 300 m spaced beach profile data. Higher current velocities were predicted in the shadow zone behind borrow areas due to gradients in wave-induced water levels and changes in wave direction induced by the dredge pits. The higher than average erosion in the southern end of the fill appears to be caused by changes in shoreline orientation and to a lesser degree, borrow area effects. Numerical modeling played a key role in understanding the observed morphological development of the fill. The use of different bathymetric scenarios proved to be a useful method in isolating the effects of each morphological feature on physical processes relevant to nourishment performance and assessing their relative effects.

This chapter is based on the following publications:

Benedet, L., Stive, M.J., Hartog, W., Walstra, D.J.R., Koningsveld, M.V., 2006. Effects of Wave Diffraction and Initial Bathymetric Conditions on Beach Fill Volume Change Predictions. In: Smith, J.M. Proceedings of the 30th International Coastal Engineering Conference, Sand Diego, California, pp 4103-4115.

Hartog, W.M. Benedet, L., Walstra, Dirk-Jan R., van Koningsveld, M., Stive, M. J.F. and Finkl, C. W. 2008. Mechanisms that Influence the Performance of Beach Nourishment: A Case Study in Delray Beach, Florida, U.S.A. Journal of Coastal Research, 24(5) 1304–1319.

3.1. INTRODUCTION

Shore nourishments are increasingly applied as a measure to counteract shoreline retreat, facilitate beach use and increase resilience to storm impact. Several beach restoration methods exist, including shoreface nourishment where submerged nearshore ‘berms’ are created (to either serve as a feeder or breaker berm) and beach nourishment where sediments are placed mostly on the subaerial portion of the beach. This last method has a direct visible effect that is readily perceived by beach users and residents, thus it is the most commonly adopted method in the world (NRC, 1995; Finkl and Walker, 2004).

In the state of Florida, southeastern U.S., beach nourishment has become standard practice to restore eroded beaches. It is of vital importance to maintenance of the beaches for tourism activities and protection of infrastructure from tropical storms and hurricanes (Finkl, 1996). Although beach nourishments are widely applied, only alongshore or plan form adjustment of the nourishment (*e.g.* Dean and Yoo, 1992; Davis *et al.* 2000) and cross-shore adjustment of the constructed profile to the equilibrium profile (as described by Dean and Dalrymple, 2002) are commonly considered in design phases to predict fill performance and lifespan. Few studies focus on the detailed morphodynamic behavior of the nourishment although alongshore variations in erosion (frequently called erosional hot and cold spots) are often reported, *e.g.* Bender and Dean (2003), Davis *et al.* (2000) and Benedet *et al.* (2006). Most research on erosional hot spots is based on analysis of beach profile data and one-line coastline models. This study illustrates how increased insight is derived from applying a ‘complex’ process-based morphological area model (Delft3D, Lesser *et al.*, 2004) to research processes that cause alongshore variability in beach nourishment response.

Based on data analysis and existing literature, several hypotheses were formulated for investigation. These hypotheses are evaluated using a detailed analysis of nearshore waves, hydrodynamic flow patterns and beach morphology changes using Delft3D. Delray Beach, a monitored beach nourishment program active since 1973, is a good case for this type of study (morphodynamic behavior of beach nourishment) due to data availability and sharp gradients in fill alongshore behavior.

In this chapter, an introduction of the study area focusing on the geologic properties of the area, the project history and previous studies performed on this particular beach is provided initially. Methodology and model set-up for are described and subsequently the model results are discussed and analyzed in three steps: (1) results of the wave modeling, (2) results of the hydrodynamic simulations and (3) results of initial morphological simulations. These results are combined in the discussion and conclusion sections.

3.2. STUDY AREA

Delray Beach is located in the southern part of the Florida Peninsula at about 80 km north of Miami Beach in the densely populated area of Palm Beach County. Nearby inlets include south Lake Worth Inlet 10 km to the north and Boca Raton inlet 13 km to the south. A location map of the study area is provided in Figure 1 with locations of the beach profile monuments maintained by the Florida Department of Environmental Protection. These are fixed beach profile measuring stations and are spaced about 300 m apart.

The Florida peninsula is the emerged part of the larger Florida platform (Bush *et al.*, 2004) that is made up mostly by limestone. On this limestone foundation the beach sand occasionally only forms a layer 1 to 2 meters thick (Finkl, 1993). The inner continental shelf extends from the 20 m isobath to the shore and is on average approximately 2500 m in width (Finkl and DaPrato, 1993). The seabed along the study area is schematically represented in the cross-section of Figure 3.2. Due to the shape of the limestone foundation the layers of sand are relatively thin on the beach and near the offshore reef (Figure 3.2). Between the beach and the reef a rather thick layer of sediment, the inter-reef in filled sand troughs (Finkl *et al.*, 2005) occurs. Sand from the in filled troughs are often dredged and used for beach nourishments.

Several shore-parallel barrier islands exist in the region. These were originally separated from the mainland by marshes, lagoons and mangrove swamps; nowadays by the artificially dredged Intracoastal Water Way (ICWW). The barrier islands are kept in place by engineering works and nearly all lack typical morphological processes of 'normal' barrier islands such as island lowering, wash-over and migration (Finkl and DaPrato, 1994; Finkl, 1994a). The beaches behave much like mainland beaches do. The ICWW is connected to the Atlantic Ocean by natural and man-made tidal inlets that are routinely dredged. The stabilization of these inlets by jetties is responsible for 80-85 % of the beach erosion problem along the Florida coast (Dean, 1990). These problems add up to the background erosion for the region, which is about 0.3-0.4 m yr⁻¹ due to sea-level rise

(Finkl,

1994b).

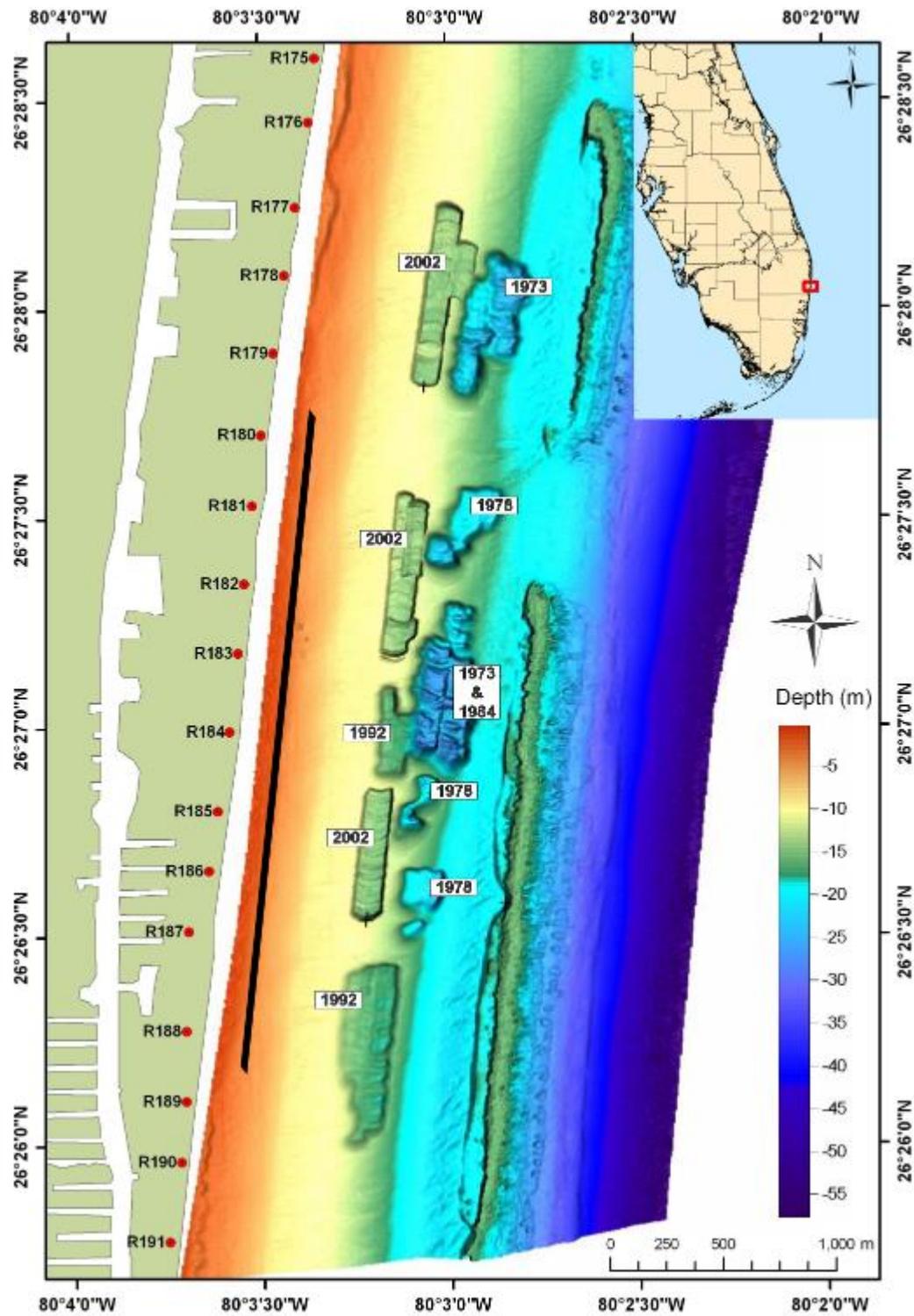


Figure 3.1 Overview of the study area (R-175 - R-191). The modeling focused on the nourished segments of 1992 and 2002 (R-180 - R-188). Shown as a 3D image is the bathymetry with the offshore parallel reef and the borrow pits. The years indicate the year in which the borrow pits were dredged.

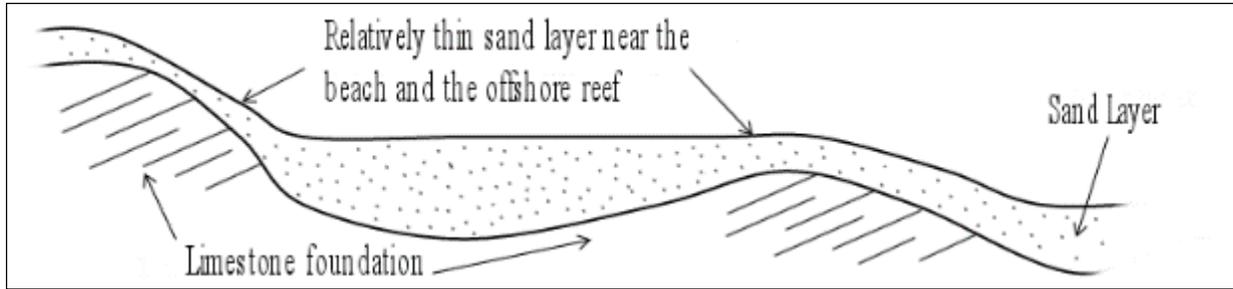


Figure 3.2. Schematized cross section of the Southeastern Florida coast. The sand layer on top of the limestone foundation is thin near the beach and offshore reef. The area in between is often used as borrow area to dredge sediment for nourishment.

3.2.1. Project History

As erosion threatened the recreational value of the beach front avenue A1A in the late 1960s and early 1970s the city council decided to sponsor a beach nourishment project. Since 1973 a comprehensive beach nourishment program has been conducted, resulting in five beach nourishments the past 20 years (Table 1). The necessary sand was extracted from dredge pits located directly offshore of the nourished beach.

Table 3.1 Delray Beach nourishment project history. (Modified from Benedet *et al.*, 2006)

Year	Volume (m ³)	Length (m)	Density (m ³ m ⁻¹)
1973	1,250,000	4,270	293
1978	536,000	2,980	285
1984	994,000	4,270	233
1992	914,500	2,730	334
2002	940,000	3,000	313

The first nourishment in 1973 created a new beach in an area where beach width was reduced to virtually zero (waves were directly hitting a rubble-mound seawall that protected the beachfront highway at the time) and was therefore the largest. The other nourishments were periodical maintenance renourishments. By 1992 the third maintenance renourishment was needed (after two in 1978 and 1984) as CPE (1992) showed that about 260,000 m³ of sand eroded from the last nourishment. The report indicated that the northern part of the project, R-175 to R-180, remained relatively stable. Therefore, the third and fourth renourishment projects (in 1992 and 2002) were only constructed in the south from R-180 to R-188A (approximately 150 m south of R-188). This study focuses on this particular shoreline segment (shown in Figure 3.1 as the black line).

3.2.2. Sediment Transport Rates

Similar to the net annual current, the net annual sediment transport is from north to south. Fernandez (1999) describes that according to Dobrowski and Mehta (1993) the sediment transport is 123,000 m³y⁻¹ at Lake Worth. Caldwell (1956) estimated the net annual sediment transport at Lake Worth Inlet at 125,000 m³y⁻¹ and 93,000 m³y⁻¹ at Boca Raton Inlet. According to Finkl (1994a) the net littoral drift at South Lake Worth inlet was 175,720 m³y⁻¹ in 1969 and 114,600 m³y⁻¹ at the Boca Raton inlet in 1981. CPE (2001) estimates net littoral transport rates for Delray Beach based on the Coast of Florida Study (USACE, 1995) and volumetric calculations. The estimated amount entering the study area, near R-175, is 72,500 m³y⁻¹. It is calculated that 47,500 m³y⁻¹ was lost on average between December 1992 and February 2000 from the study area. Therefore the net littoral transport was about 120,000 m³y⁻¹ at R-191 during this period.

3.3. PREVIOUS STUDIES

Areas with localized high erosion are often described as erosional hot spots: areas that erode significantly more than the project average erosion. Several authors (Benedet *et al.*, 2007; Fernandez, 1999; Gravens 1997) reported the existence of erosional cold and hot spots along the nourished area of Delray Beach. Benedet *et al.* (2007) discusses the identification and parameterization of erosional hot spots by several authors (*e.g.* Liotta, 1999), Stauble, 1994 and Finkl and Kerwin, 1997) and defines criteria to identify erosional hot spots at Delray Beach. He concludes that there is a pronounced variability of response alongshore and that the segment R-186 - R-187 is an erosional hot spot. The variation in sediment transport alongshore is also visible in Table 3.2 (based on data analysis of beach volume change), where standard deviations twice as large as the volume changes indicate large variability of morphological evolution between different fill segments.

Table 3.2. Average volume changes in m³m⁻¹ and the standard deviation in m³m⁻¹ for individual monuments, the total fill and the erosional hot spot (R-186 - T-187) for two periods: Dec '93 - Jan '01 (includes the first two years of adjustment after the 1992 nourishment) and Dec '95 - Jan '01.

Monument	Dec '93 - Jan '01		Dec '95 - Jan '01	
	ΔV (m ³ m ⁻¹)	SD (m ³ m ⁻¹)	ΔV (m ³ m ⁻¹)	SD (m ³ m ⁻¹)
180	4	43	7	46
181	-2	86	24	85
182	-18	39	-6	11
183	-28	42	-15	43
184	-21	31	-14	32
185	-11	67	-9	43
186	-46	55	-22	37
187	-46	79	-18	37
188	-5	48	6	47

Fill	-19	60	-5	46
186-187	-46	68	-20	35

Fernandez (1999) used the one-line model DNRBSM (Dean and Grant, 1989) to identify segments that performed atypically in this project. This author defined a cold spot (area that eroded less than predicted by the model) near R-178 and an erosional hot spot (area that eroded more than predicted by the model) at R-187. Differences in grain size were suggested as a possible cause of the occurrence of hot and cold spots at these beach segments. However, the grain size distribution along Delray Beach does not show a persistent finer size at R-187 or persistently coarser at R-178 as discussed in Benedet *et al.* (2007).

Gravens (1997) studied the effects of the bathymetry and wave conditions on predicted shoreline positions with the one-line model GENESIS (Hanson and Kraus, 1989). Simulations were conducted using representative offshore as well as nearshore wave conditions. These nearshore wave conditions were obtained by evaluating the wave transformation over the measured nearshore bathymetry using the monochromatic wave model RCPWAVE (Ebersole, 1985; Ebersole *et al.*, 1986). Simulations with the nearshore wave conditions provided results that compared better with measured shoreline changes indicating a significant influence of the nearshore bathymetry on shoreline behavior. Gravens (1997), however, indicates that the use of a spectral wave model may provide a more realistic representation of the nearshore wave conditions.

3.4. METHODOLOGY

3.4.1. Hypothesis Evaluated

Several hypotheses have been raised to explain the erosional hot spots at Delray Beach (Fernandez, 1999, Gravens, 1997, Benedet *et al.*, 2007). Fernandez (1999) hypothesized that grain size differences might cause erosional hot spots, Gravens (1997) identified shoreface bathymetry as an important factor in the morphodynamics of Delray Beach and Benedet *et al.* (2006) indicated the importance of shoreline orientation on nourishment behavior, suggesting the change in shoreline orientation at the southern end of the nourishment as a possible cause of the erosional hot spot at this location. To further investigate the effects of bathymetric features on nourishment behavior, the process-based model Delft3D (including the directional spectral wave model SWAN) was used. This allowed mathematical manipulation of the bathymetry in order to evaluate its effect on beach nourishment performance. The following main hypotheses were evaluated.

- a. *The man-induced borrow pits influence the nearshore wave climate;*
- b. *Variable wave heights and directions caused by item 'a' cause alongshore differences in sediment transport and control the location of the erosional hot spot.*
- c. *The variation in shoreline orientation causes alongshore differences in sediment transport and controls the location of the erosional hot spot.*

These hypotheses were investigated in three steps: (1) Analysis of wave transformation using the numerical wave model SWAN, (2) Analysis of hydrodynamics using the depth averaged flow module of Delft3D and (3) Analysis of the combined effects of waves and currents on sediment transport and beach morphology changes use the morphology module of Delft3D.

3.4.2. Delft3D Overview

The Delft3D model is a process-based model containing a detailed description of relevant processes such as waves, tide, currents and sediment transport and the interaction with each other. This interaction may cause a varying flow field and bed level changes. The Delft3D-online module performs the hydrodynamic computations and simultaneously (“online”) calculates waves, transport of sediments and updates the bathymetry.

The model makes use of the SWAN (Simulating Waves Nearshore, Holthuijsen *et al.*, 1993) model for the WAVE-module. The mean wave directions are computed by the wave model SWAN after which the energy associated with the waves propagating shoreward is computed.

The FLOW-module provides the hydrodynamic basis for many cases in coastal environments. In Lesser *et al.* (2004) a detailed description is given of the online version of the FLOW-module and its applications. The FLOW module is a hydrodynamic flow simulation program that simulates transport phenomena and solves the unsteady shallow-water equations in 2DH (depth-averaged) or 3D. In the module phenomena as tide, wind and wave driven flows, stratified and density flows are included in situations where bottom level, water level and velocity field change significantly during a flow simulation. Recent modifications in the FLOW module included three dimensional wave effects as wave-induced mass flux, wave-induced turbulence, streaming and forcing due to wave breaking (Walstra *et al.*, 2000).

For sediment transport a new approach has been implemented. Instead of using the modules Delft3D-SED and -MOR the sediment online version continuously updates transport of sediments and therefore is possible to change the bed level and give feedback to the hydrodynamics. For the transport of sediments two types of sediment transport are computed. Over the entire water column the suspended sediment is computed and for a reference height above the bottom the bed load transport is computed. The sediment transport module uses the approximation method of VAN RIJN (1993).

Morphodynamic development time scales are significantly larger than those of hydrodynamic time scales. The morphological acceleration factor (Morfac) is therefore used so only for a fraction of the duration the hydrodynamic simulations are required. In this way the speed of changes in the morphology is scaled up to a rate where it begins to have a significant impact on the hydrodynamics and the computational time can be reduced.

3.4.3. Numerical Model Computational Grids

Three computation grids were created for this numerical modeling effort, a larger regional SWAN grid, a SWAN grid with greater resolution at the study area, and a detailed grid used to calculate flows, sediment transport and morphological change. To transform waves from deepwater to shallow water, the larger regional SWAN grid (20 x 5 km) was created (Figure 3). This larger grid consisted of cells of 250 x 250 m and provided boundary conditions for the smaller, detailed SWAN. Open north, east and south boundary conditions were pre-defined as input data. The 'fourth' boundary is formed by the shoreline in the west. The detailed SWAN grid had cells of 100 x 100 m near the boundaries and refined to 25 x 25 m towards the area of interest. A detailed grid with smaller cell sizes (15 by 15 m) was utilized for the hydrodynamic Flow and sediment transport calculations. Towards the three open boundaries (north, east and south) the grid gradually coarsens, with maximum sized cells of about 30 x 30 m. All simulations were performed done in '2DH' mode, which means that the grid consists of only one vertical layer and the velocity is depth averaged. Cross-shore processes are taken into account, but approximated with the depth averaged calculations.

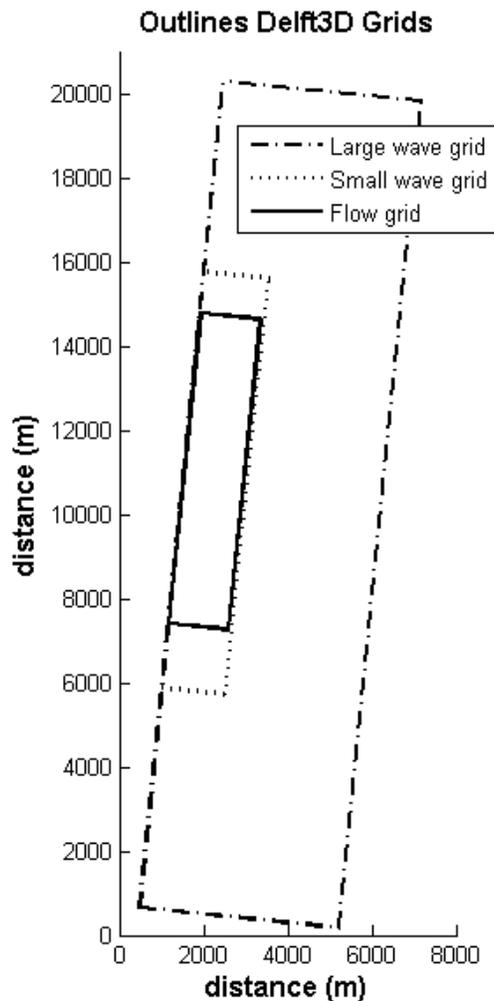


Figure 3.3 Overview of the grids used for the Delray Beach model. From large to small respectively the large wave grid, the small wave grid and the flow grid.

3.4.4. Numerical Model Bathymetry

Laser Airborne Depth Sounder (LADS) bathymetric data was used as the main model input to create the model surface (.dep file). This data was collected six months after the 2002 beach nourishment project and consisted of over 1 million sample points covering an area of approximately 10 x 2.5 km. Since the first nourishment in 1973 sand has been mined from the seabed just offshore of the beach nourishment project area. The dredge pits are noticeable in bathymetric images of the project area (*i.e.* see Figure 1). The dredge pits dredged in 1973 and 1978 contain deeper depths of cut, when compared to the most recent pits (1992 and 2002) due to lack of controls during that time. The older Dredge pits show depths of cut are as deep as 8 m below the seabed (16 m below the water surface elevation). The borrow pits did not fill in by natural sediment transport processes since dredged as shown in Figure 1, this is most likely attributed to the fact that these dredge features are located seaward of the active profile depth (depths greater than 10 m). Another noticeable offshore bathymetric feature is the gap in the offshore reef system, which is located about 1400 m offshore in the northern limit of the beach nourishment area.

3.4.5. Bathymetric Modifications

Mathematical adjustments to the model input bathymetry, consisting of selectively infilling the dredge pits (Figure 3.4), modifying the offshore reef gap, and modifying beach fill planform and shoreline orientation.

The following scenarios of modified bathymetries were simulated: (1) original bathymetry; (2) modified bathymetry with infilled deeper-cut dredge pits; (3) modified bathymetry with all dredge pits infilled; (4) modified bathymetry with gap in the reef system replaced by a continuous reef, (5) modified bathymetry with offshore shore-parallel reef completely removed; (6) modified bathymetry with surf-zone data replaced by equilibrium profile; and (7) modified bathymetry with curved fill-induced shoreline replaced by a straight coast.

These bathymetric manipulations were conducted to evaluate the effects of were conducted of shoreline orientation, surf-zone morphology and offshore bathymetric features on the nearshore wave climate, hydrodynamic flow patterns and beach erosion and sedimentation trends at the study area. Specifically, bathymetric scenarios 2 and 3 were developed to evaluate the effect of the offshore dredge pits, scenario numbers 4 and 5 were developed to evaluate the effect of the offshore shore-parallel reef system, bathymetric scenario number 6 was conducted to evaluate the effect of fill-induced surf-zone morphology while scenario number 7 was developed to evaluate the effect of fill-induced shoreline orientation.

Manipulation of offshore features utilized in scenarios 2 to 5 is illustrated in Figure 3.4. The equilibrium profile utilized in scenario 6 was derived from field measurements. Figure 3.5 shows all beach profiles available for the fill area (R-180 to R-188) measured in the years of 1999, 2000 and 2001 and converted into one data set delimited by the NVGD +3.0 m (National Geodetic Vertical Datum, USACE, 2002) and the NVGD -10.0 m contour. It was assumed that these profiles, measured 7, 8 and 9 years after the nourishment respectively, are a good approximation of the equilibrium profile of the study area. Using this data set a polynomial was fitted (grey line in Figure 3.5) and this polynomial was assumed to represent the equilibrium profile of Delray Beach between profile monuments R-180 and R-188. This equilibrium cross-shore profile was

used in two scenarios in scenario number 6 all bathymetry values were replaced by the polynomial between the NVGD +3.0 m and the NVGD -10.0 m contours and the NVGD 0.0 m crossing was maintained at the same x-coordinate as the original bathymetry thus the original shoreline orientation was preserved while in scenario number 7 all bathymetry values were replaced by the equilibrium profile polynomial fit above the approximate NVGD -10 m contour with the same x-coordinate origin, so a straight coast was developed.

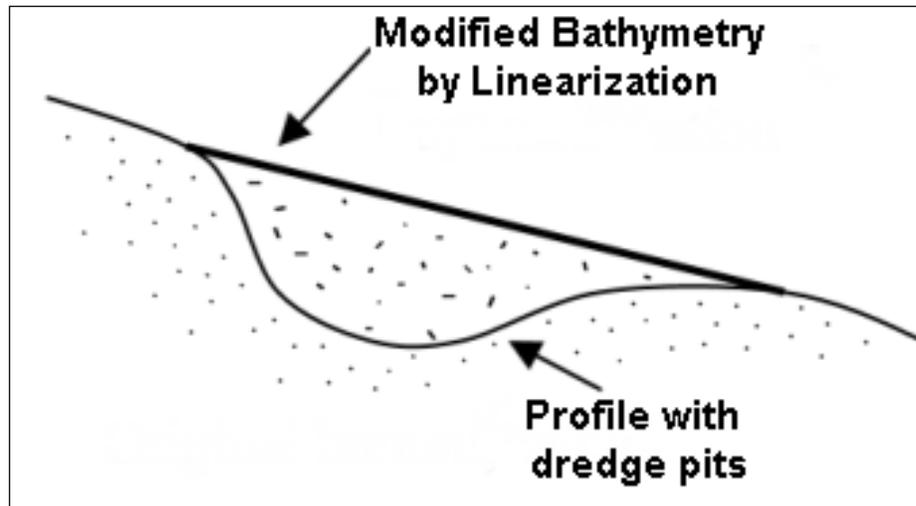


Figure 3.4. Schematized cross section view of the method to modify the bathymetry. By linearization the bottom is reshaped to the pre-dredging condition.

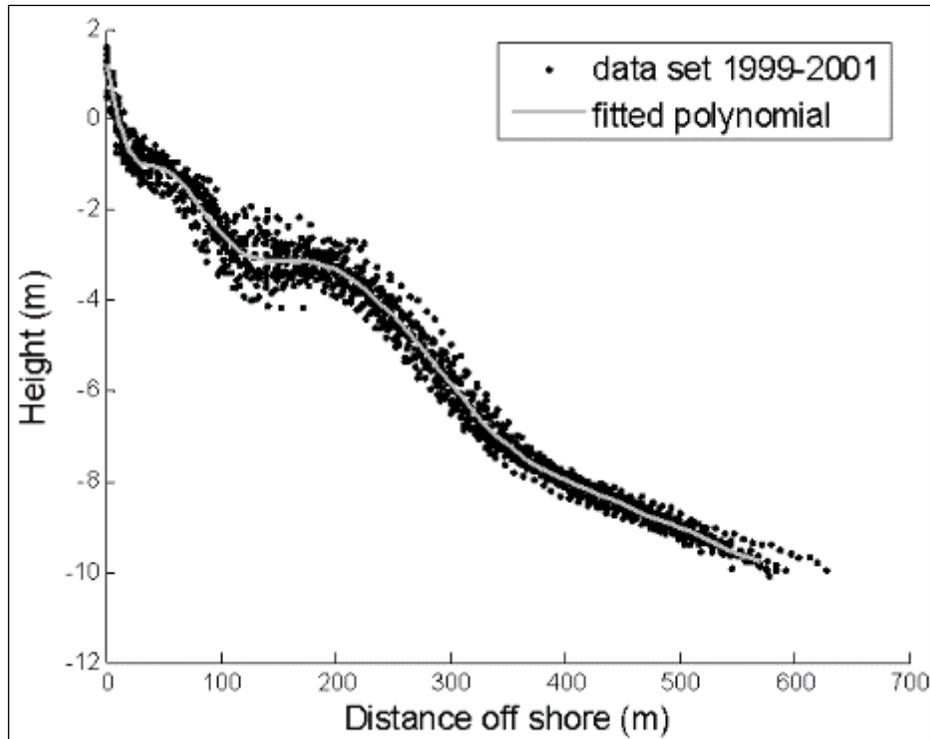


Figure 3.5. Equilibrium profile measurements for the nourished area (R-180 - R-188). The grey line represents a polynomial fitted through all available measurements in the period 1999 - 2001, 7 to 9 years after the nourishment, for all DNR monuments R-180 to R-188.

3.4.6. Met-Ocean Boundary conditions

Wave, tide and wind conditions were obtained by analyzing the data of four local met-ocean stations (all located within a 15 km range of the study area). The wave conditions at the SWAN grid boundaries were obtained from wave hindcast study developed by the U.S. Army Corps of Engineers, WIS station #463 (USACE, 2007), this data was provided at 60 minutes interval, from from 1980 to 1999. To differentiate between wind waves and swell waves the peak period, T_p , was used. A JONSWAP spectral space shape was used, for the purpose of wave and flow analysis a set of wave conditions was selected within seven direction sectors, each 30° wide. Two wave heights were chosen to represent an average condition and an extreme wave condition per direction band. Fourteen wave cases resulted from this analysis to represent an annual wave climate based on 20 years of wave statistics. The wave climate represents all important conditions along the study area, including most-frequent waves, northeasters and hurricanes. After an evaluation and calibration of simulated sediment transport patterns the wave climate was reduced to six conditions, representing a morphologic year. Therefore six wave conditions were used to perform the morphologic analysis reported hereinafter.

Water level and flow conditions were set in the FLOW module. Nine years of water level data, from 1995 to 2004, obtained at Lake Worth were analyzed to obtain the tidal range; MHW occurs at NGVD + 0.52 m, MSL at NGVD + 0.12 m and MLW at -0.29 m. No literature was found that mentions a horizontal component of the tide being present. The FLOW model east boundary

is an open boundary where the water level is given by the harmonic representation of the tide with an equilibrium elevation of NVGD +0.12 m and an amplitude of 0.40 m. The north and south boundaries are called Neumann boundaries (Roelvink and Walstra, 2004). It is common in hydrodynamic flow modeling to use the water level or the current velocity as the boundary condition. Instead, in this model the water level gradient is used as lateral boundary conditions. In this case, the gradient equals zero at all times, which means that the water level has the same level as in the adjacent cells and the currents flow ‘through’ the boundary (Roelvink and Walstra, 2004).

To allow the simulation spin-up time, two days are simulated, which allows the model to complete almost four tidal cycles. For hydrodynamic simulations a time step of 60 s was used. The use of sediment transport requires a few modifications and additions (concerning the sediment transport) to the model set-up. Simulations were made with the same grid and depth files as used for the hydrodynamic flow analysis. For the sediment transport related boundary conditions all values were set on 0. This means that there initially is no in- or outflow of sediment forced through the boundaries. The Neumann boundaries were used so that there was no gradient in sediment transport through the boundaries the rest of the modeling time. This was expected to be acceptable for the purpose of this study, as the model is allowed ‘spin-up’ time (to bring sediments in suspension) and boundaries are located far enough from the area of interest. The time step was reduced to 12 s in order to improve the accuracy of the model when sediment transport simulations were carried out. A sensitivity analysis was performed in order to optimize computing time and the accuracy of the results.

Because of the geographic location of Delray Beach, west and southeast winds have little influence on coastal dynamics. West winds blow from land (offshore winds), thus does not create waves. Southeast or east winds have a limited fetch (due to the position of the Bahamas) and therefore generate only milder short period waves when compared to waves from the northeast. For numerical modeling purpose a similar wind climate as the wave climate was created. For every direction sector an average and an extreme wind velocity was selected.

The average sediment grain size of the project area 0.30 mm was used for sediment transport modeling. Although the mean grain size varies greatly across the beach profile in the study area (*i.e.* Benedet et al., 2006) this grain size value resembles a weighted average of samples collected across the entire beach profile.

3.5. RESULTS OF WAVES STUDIES AND HYDRODYNAMIC SIMULATIONS

3.5.1. Nearshore Wave Simulations

Fourteen wave conditions were simulated in this study, the results for three of these fourteen wave conditions, as shown in Figure 6, demonstrates an overview of the influence of the effects of the offshore bathymetry on the wave climate.

In figure 3.6A prominent alongshore variation in the alongshore wave height is observed, this figure corresponded to the simulation of a ENE swell event, with H_s of 2.00 m, T_p of 11.5 s, and 60° direction of approach. These alongshore variations are mainly due to refraction caused by the offshore bathymetric features, most importantly the dredge pits. When waves from the NE

propagate over the dredge pits, they refract towards the edges of the pits, causing lower waves behind the pit and increasing the significant wave height in between the sheltered areas behind two consecutive dredge pits. For average (most frequent) wave conditions (*e.g.* $H_s = 0.8$ m, $T_p = 5.5$ s, 45° , as shown in Figure 3.6B) the refraction patterns are hardly noticeable and are considered negligible. The fluctuations in wave height are also less pronounced for short-period southeastern waves when compared to longer period northeastern waves; *e.g.* compare Figure 3.6C ($H_s = 1.85$ m, $T_p = 8.5$ s, 135°) with Figure 3.6A. These different wave distribution patterns are mostly caused by differences in wave period between these two events.

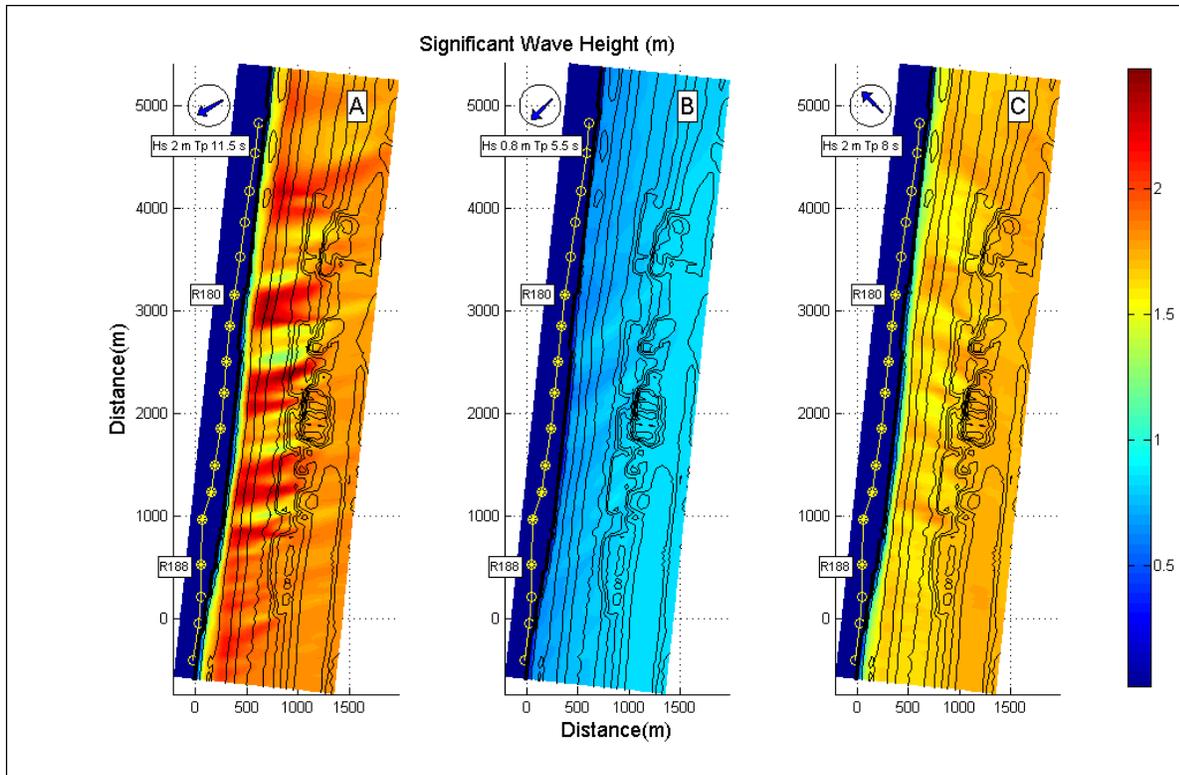


Figure 3.6. Significant wave height for three wave conditions and the original bathymetry. (A) $H_s = 2.00$ m, $T_p = 11.5$ s, 60° (B) $H_s = 0.75$ m, $T_p = 5.5$ s, 45° (C) $H_s = 1.85$ m, $T_p = 8.5$ s, 135°

3.5.1.1. Influence of the borrow pits on nearshore waves

The same wave condition displayed in Figure 3.6A ($H_s = 2.00$ m, $T_p = 11.5$ s, 60°), simulated over a reconstructed bathymetry (with all dredge pits infilled) is shown in Figure 7. The nearshore wave height distribution displayed in the no-dredge pit scenario (Figure 7) is largely different from that after 2002 conditions as displayed Figure 3.6A. The large sheltered areas have disappeared in the no-dredge pit scenario, although a few fluctuations in wave height are still visible (due to some remaining bottom irregularities) the effects of the pits, especially those dredged in 1973 and 1978, are evident. The older dredge pits have a greater influence on the nearshore waves because they have deep depths of cut causing more wave refraction relative to the more recent elongated dredge pits that have shallower cuts.

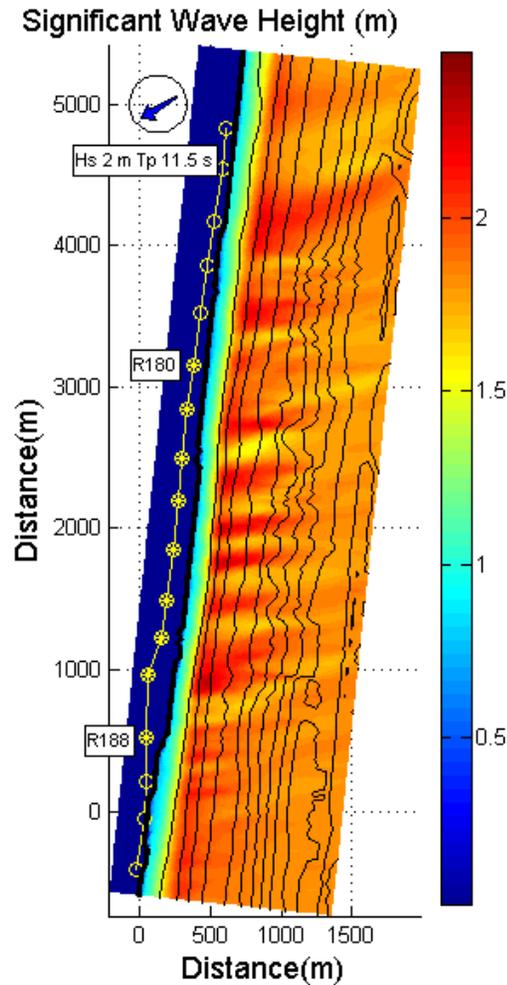


Figure 3.7. Significant wave height for the wave condition $H_s = 2.00$ m, $T_p = 11.5$ s, 60° and the adjusted bathymetry without borrow pits.

3.5.1.2. Influence of the shore-parallel reef on nearshore waves

Gravens (1997) suggested the offshore reef as a possible cause for the erosional hot spots along the study area. The influence of the reef was investigated using bathymetric scenarios with/without the reef and with/without reef gap. The significant wave height alongshore, at approximately 120 m offshore in the outer surf-zone, for four bathymetric scenarios is shown in Figure 3.8. The result corresponds to the simulation of the ENE wave case displayed in Figures 3.6A and 3.7 (simulations with $H_s = 2.00$ m, $T_p = 11.5$ s, 60°). The scenarios represented include the original 2002 bathymetry, a hypothetical continuous reef situation (no reef gap), a situation with no offshore reefs and lastly the scenario with all dredge pits removed (infilled). Hardly any differences between simulations with the 2002 bathymetry and simulations with modified reef configurations can be observed, however large differences between all scenarios and the no dredge-pit situation are

observed. This result demonstrates that the direct influence of the shore-parallel reef system, particularly the reef-gap on the nearshore wave climate is negligible relative to the effect of the dredge pits (also displayed in Figure 3.8).

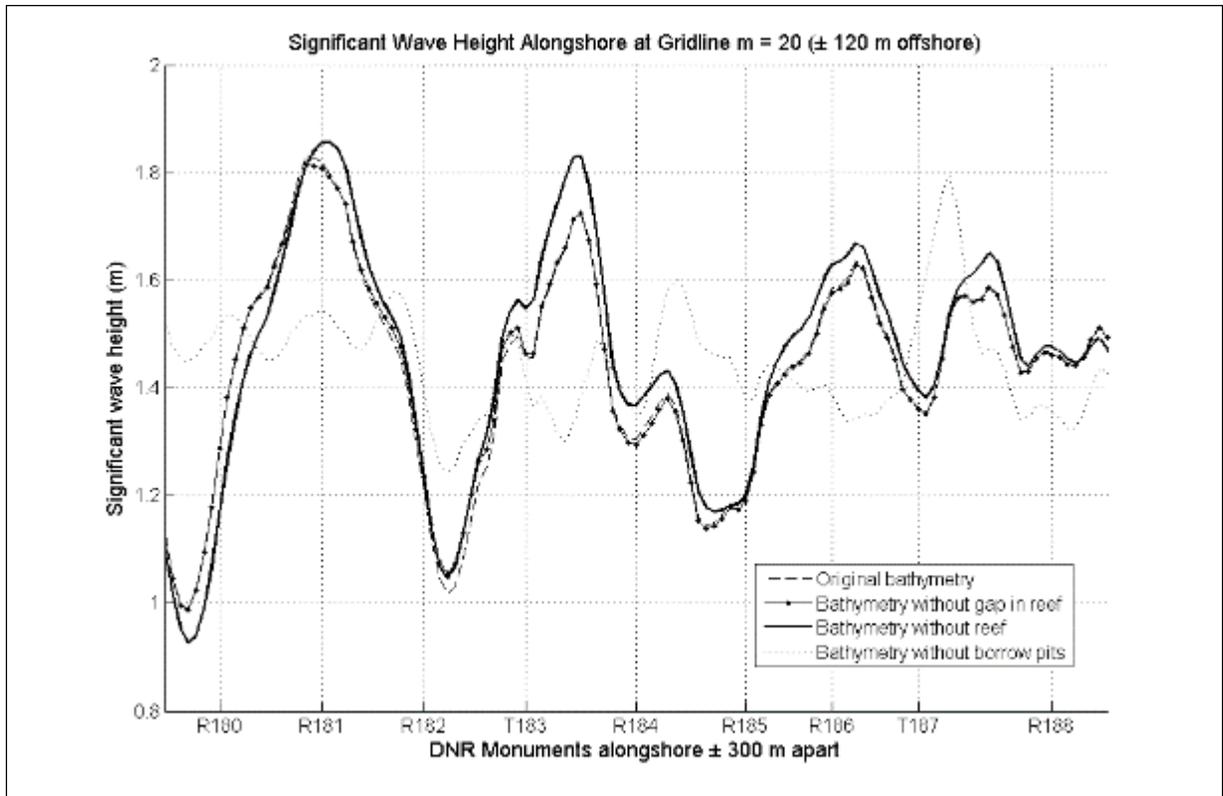


Figure 3.8 Significant wave height alongshore at gridline $m = 20$ (approx. 120 m offshore) for wave condition $H_s = 2.00$ m, $T_p = 11.5$ s, 60° and four different bathymetries: (1) the original bathymetry, (2) a bathymetry with a continuous reef (so without the gap), (3) a bathymetry without the reef and (4) the bathymetry without borrow pits.

3.5.1.3. Diffraction, reflection and bottom friction

The gradients caused by the refraction decrease as the wave energy ‘spreads out’ along the wave crest due to diffraction. Diffraction was not explicitly modeled in the SWAN version used for this study, *viz.* SWAN version 40.30 (latest SWAN version 40.41 includes a simplified formulation of diffraction for a spectral wave model). Diffraction effects can be partly simulated by applying a wide directional spreading of waves. However, after initial tests it was considered to be of more importance to use a narrow direction spreading as the most important wave conditions in the study area (high northeastern waves) are long-period ‘swell’ waves with a narrow directional spreading. This model therefore did not take diffraction into account.

Bender and Dean (2003) reviewed “studies on wave transformation by bathymetric changes and the resulting shoreline impacts”. One of the conclusions of these authors was that few wave models include reflection by borrow pits, while this process may have significant impact on modeling results. Reviewed studies about reflection from borrow pit sidewalls were predominately

conducted on borrow pits with steep (often vertical) sidewall slopes and located in relatively shallow water. Michalsen *et al.* (2005) makes a comparison between borrow areas with steep and mild slopes (1:10) in shallow water ($kh=0.24$) and concludes that “wave reflection is important even in cases where the sidewall slope is mild”. The borrow pits at Delray Beach have mild sidewall slopes, the maximum steepness is 1:7 and the average is 1:10. However, the borrow pits with the largest influence at Delray Beach are located in a water depth of at least 16 m. The longest waves with a peak period of 11.5 s cannot be considered to be in shallow water at these depths ($kh = 0.49$), but in transitional waters (Dean, 1970; Le Mehaute, 1976). The reflection effects of the borrow pits at Delray Beach are therefore considered negligible in this study.

Leadon *et al.* (2004) studied deep water wave transformation over the Cape Canaveral Shelf (Central-East coast of Florida) and found that model simulations with bottom friction significantly improved comparisons between *in situ* nearshore wave measurements and model results. Leadon *et al.* (2004) obtained results with an adjusted STWAVE model (Smith *et al.*, 2001), using a “realistic value of 0.023 for the friction coefficient”. In these Delft3D simulations however, the default option for bottom friction was used, JONSWAP (Hasselmann *et al.*, 1973) with $C_{JON} = 0.067 \text{ m}^2\text{s}^{-3}$. Tests with different bottom frictions showed a maximum deviation of 0.03 m in wave height, about 1% to 2% of input boundary conditions. The default value for bottom friction was therefore used for all simulations.

3.5.2. Hydrodynamic Simulations

Alongshore variability in current velocities are observed due to a combination of several processes including wave focusing and shadowing and changes in wave direction due to wave transformation processes over the irregular offshore bathymetry, and changes in shoreline orientation due to the anomaly induced by the beach nourishment project.

Relative higher waves at, for example, R-180 (Figure 3.9A) causes higher wave set-up at this location (Figure 3.9C). The wave set-up gradually becomes lower southwards (due to lower wave heights). This gradual head difference causes acceleration of the southbound current as indicated in Figure 3.9B. Further south (R-183) the current meets another area of higher waves (thus higher wave set-up) and the current decelerates. The same process repeats southward in other areas where high variability in alongshore wave heights exist. Wave set-up differences are visible throughout the study area, wave focusing generates water levels at +0.7 m NVGD, while in the non-set up areas the water level is about + 0.65 m NVGD. These differences result in significant water level gradients alongshore of 0.05 m over 400 m.

In addition to this hydraulic head difference the changes in wave direction due to the refraction (the wave rays bend away from the borrow pit) contributes to current acceleration downdrift of the borrow areas during northeastern wave events (Figure 3.9D).

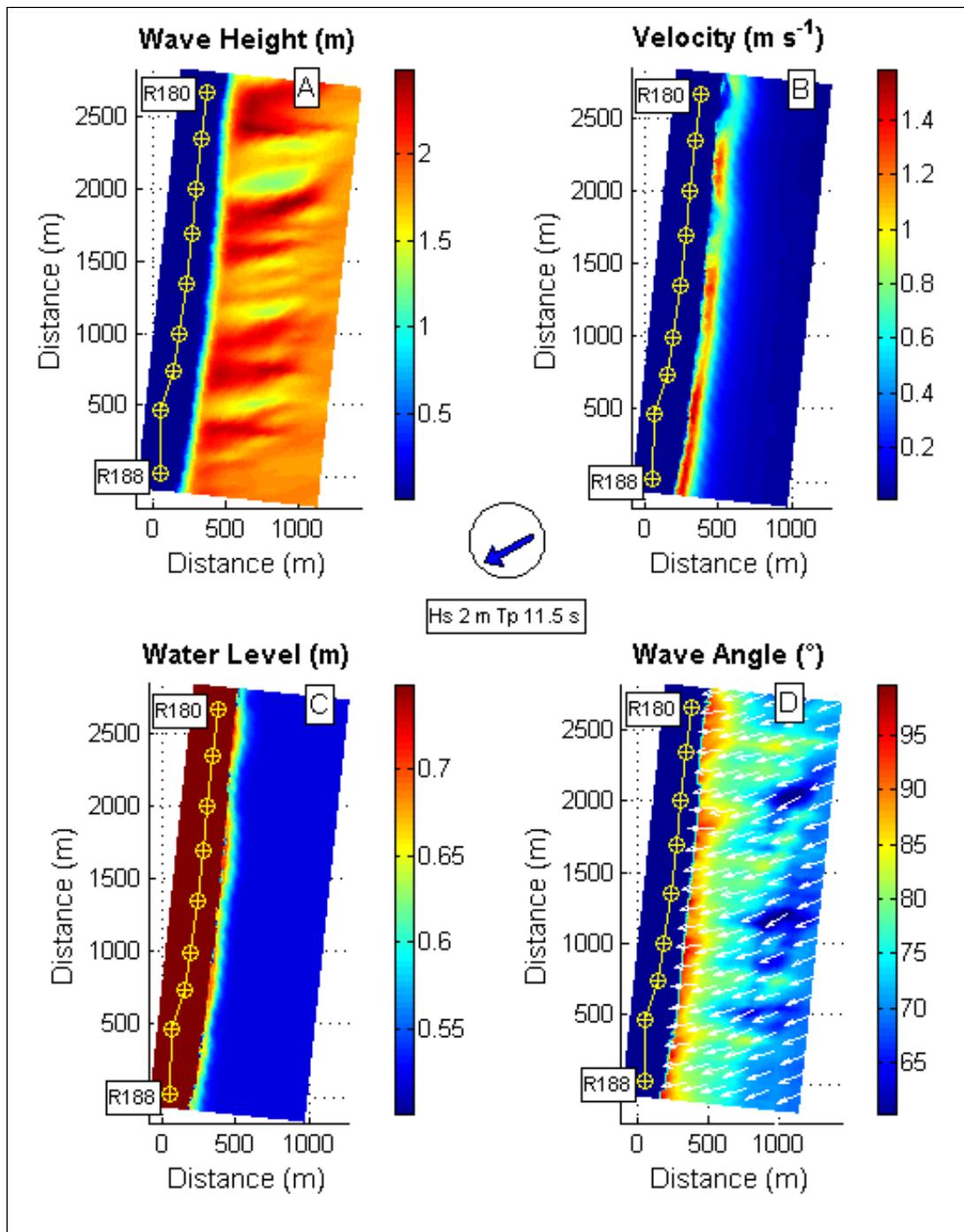


Figure 3.9. Wave and hydrodynamic results for the scenario utilizing original bathymetry and wave condition $H_s = 2.00$ m, $T_p = 11.5$ s, 60° . (A) The significant wave height, (B) the current velocity, (C) the water level and (D) wave angle.

The above-described processes cause variations in alongshore current velocity during high wave conditions, especially those associated with longer peak wave periods. When shore perpendicular waves (Figure 3.10-A, $H_s = 1.85$, $T_p = 9.5$ s, 90°) are simulated cross-shore currents are observed, some extending offshore for almost 500 m (Figure 3.10-A). These cross-shore

currents are caused by differences in wave set-up which in turn are caused mostly by wave refraction over the irregular bathymetry. Although these cross-shore flow patterns were predicted in the model, no field measurement exists to corroborate its occurrence.

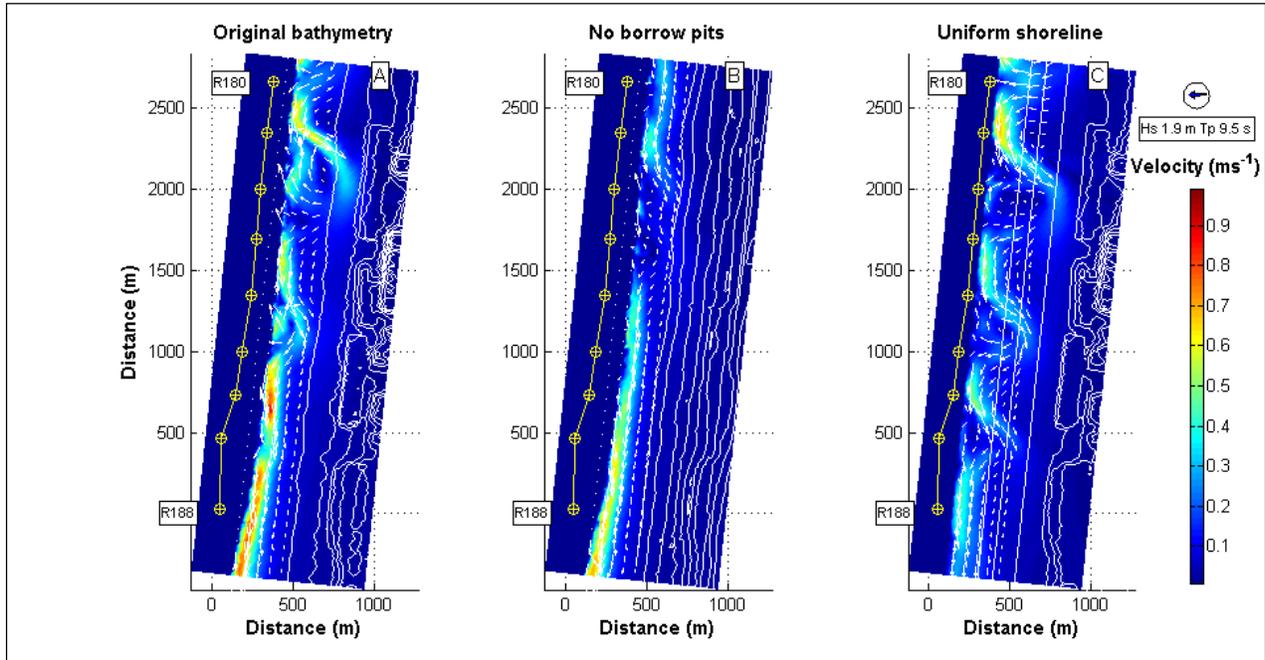


Figure 3.10. Current velocity for simulations with wave condition $H_s = 1.85 \text{ m}$, $T_p = 9.5 \text{ s}$, 90° and three different bathymetries: (A) the original bathymetry, (B) a bathymetry without borrow pits and (C) a bathymetry with uniform shoreline.

The depth-averaged current velocity for a bathymetric scenario re-constructed to resemble the pre-1973 nourishment project (no borrow pits) is shown in Figure 3.10-B. Compared to Figure 3.10-A (existing conditions) it can be noticed that the prominent cross-shore currents are no longer visible. The increased velocities in the south end persists in the no dredge-pit scenario (Figure 3.10-B), but is of smaller magnitude when compared to the existing conditions (Figure 3.10-A).

The depth averaged velocity for the bathymetric scenario with an artificially created uniform shoreline is shown in Figure 3.10-C. Compared to the scenario with the shoreline induced after the 2002 beach nourishment project (Figure 3.10-A) it can be observed that current velocities simulated in the south end of the project are of smaller magnitude in the straight shoreline scenario. The reason attributed here for lower velocities in the scenario displayed in figure 3.10-C (straight shoreline) is that the fill induced ‘bend’ in shoreline orientation observed in this location has been smoothed out and the waves are now almost shore-normal in this location.

The features that control the current patterns simulated after for the bathymetric scenario corresponding to the situation after the 2002 beach nourishment project (Figure 3.10-A) are therefore broken down into two: (1) offshore borrow areas and (2) fill-induced shoreline orientation. One prominent feature is the acceleration of flows in the south end of the borrow site,

which is correlated to the EHS location. This acceleration is observed in both reconstructed scenarios (no dredge pit as shown in Figure 3.10-B and straight shoreline as shown in Figure 3.10-C), albeit with smaller magnitudes when compared to a situation when these two features (dredge pits and fill induced shoreline orientation) occur simultaneously (Figure 3.10-A).

Simulations with a scenario that consists of a surf-zone made of a typical equilibrium profile were also conducted. The equilibrium profile scenario shows lower maximum alongshore velocities and wider surf-zone. This difference can be explained by the morphology of the surf-zone associated with the equilibrium profile scenario (equilibrium profile bathymetry is flatter than the post construction bathymetry). This flatter beach profile causes a wider surf zone, with a wider alongshore current zone and associated lower maximum velocities. But since these effects apply to the entire, it is not identified as a cause for local differences in sediment transport and beach erosion and sedimentation changes.

3.6. ANALYSIS OF MORPHOLOGY CHANGE SIMULATIONS

3.6.1. Morphological Model Performance

A comparison between alongshore transport rates calculated from the one year simulations and literature values was made. In Figure 3.11 the alongshore sediment transport calculated by Delft3D with bathymetry updating is shown. The simulation represents the total sediment transport for a year averaged wave climate. The average estimated transport rate on a stable part of this segment of the coast is about $130,000 \text{ m}^3\text{y}^{-1}$. This number includes a sediment pore volume and therefore the sediment volume without pore space is $80,000 \text{ m}^3\text{y}^{-1}$.

The model shows a net sediment transport in southward direction (as reported in literature, *e.g.* Fernandez, 1999), indicated by the negative transport values. The values on the stable part of the study area (R-175 – R-180) match well with reported values. A strong peak however in sediment transport rates is observed in the south of the study area (between R-185 and R-189) which reaches rates above $180,000 \text{ m}^3\text{y}^{-1}$. This peak may be explained by the fact that the beach nourishment of 2002 (as the one in 1992) was placed between R-180 and R-188A (halfway R-188 and R-189). This change in shoreline orientation at the end of the fill causes stronger alongshore currents and an increase in sediment transport rates at the location of the erosional hot spot. The decrease in transport magnitude between R-182 and R-183 is attributed to the influence of the borrow pits.

Further validation was performed comparing model results with observed beach volume changes. The volume changes can be calculated integrating the bottom change for each grid cell for the total study area. In order to validate the model these volume losses were compared with measured volume losses calculated from beach profiles. Measured volume changes were derived from a single cross section for every DNR Monument making the volume change for the entire study and fill area an approximation. The totals show that the simulated total volume change in the fill area slightly overestimated the measured one ($170,000 \text{ m}^3\text{y}^{-1}$ vs. $160,000 \text{ m}^3\text{y}^{-1}$), but that the volume changes for the total study area differs by a factor of two ($225,000 \text{ m}^3\text{y}^{-1}$ vs. $110,000 \text{ m}^3\text{y}^{-1}$). The losses predicted outside the fill area do not compare with reality as the adjacent non-nourished areas are more stable in practice. The alongshore sediment transport showed unrealistic large gradients towards the boundaries of the model causing large erosion outside the fill area. This is believed to be due to boundary effects of the model or the larger grid cell size used in this zone. The grid cells were set gradually larger towards the boundaries, decreasing the accuracy of

the model. Results within the fill area were considered to be accurate enough for further analysis; results outside the fill area were not used in this study.

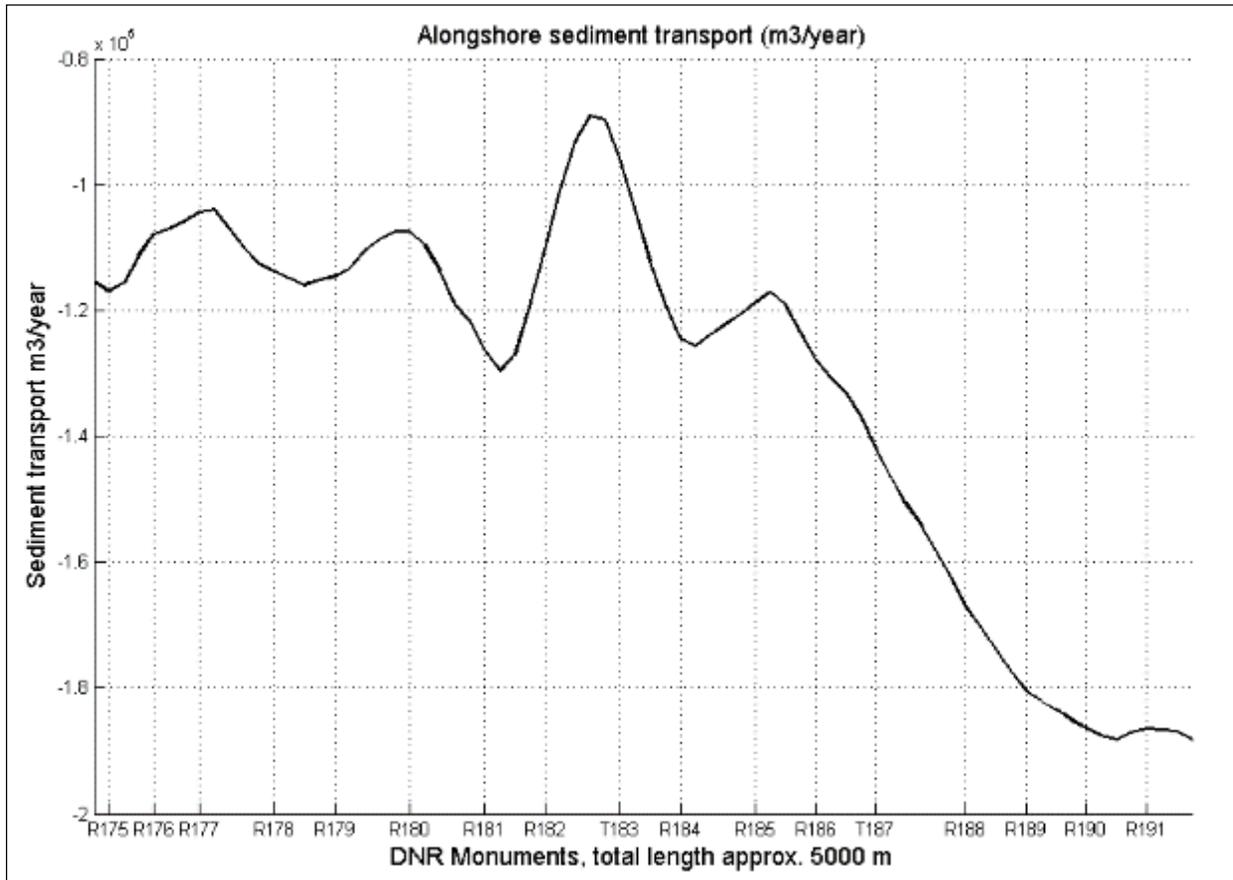


Figure 3.11. Alongshore sediment transport for a simulation with an averaged morphologic year simulated with 6 wave conditions, which were based on the 14 wave conditions derived from available hindcast wave data.

3.6.2. Results from morphologic changes

Erosion and deposition patterns after one year of beach morphology change are shown in Figure 3.12. The one year simulations used six wave conditions and represent an average annual wave climate. The beach segment located at the south of the fill (the fill area is visible as the solid dots in Figure 3.12) is subject to erosion of up to 4 m (Figure 3.12), while less sedimentation on the foreshore is present on this segment (matches with the erosional hot spot: R-186 - R-187). One would expect a certain amount of sedimentation in the surf zone on this area due to the adjustment of the cross-shore profile of the initially steeper nourishment by cross-shore transport. The alongshore current and related sediment transport, however control the profile adjustment; inhibiting cross-shore transport and surf-zone deposition. Although higher erosion in the south end of the fill is observed in the model, the magnitude of the erosion in the hot spot area (R-186 - R-187) is slightly underestimated.

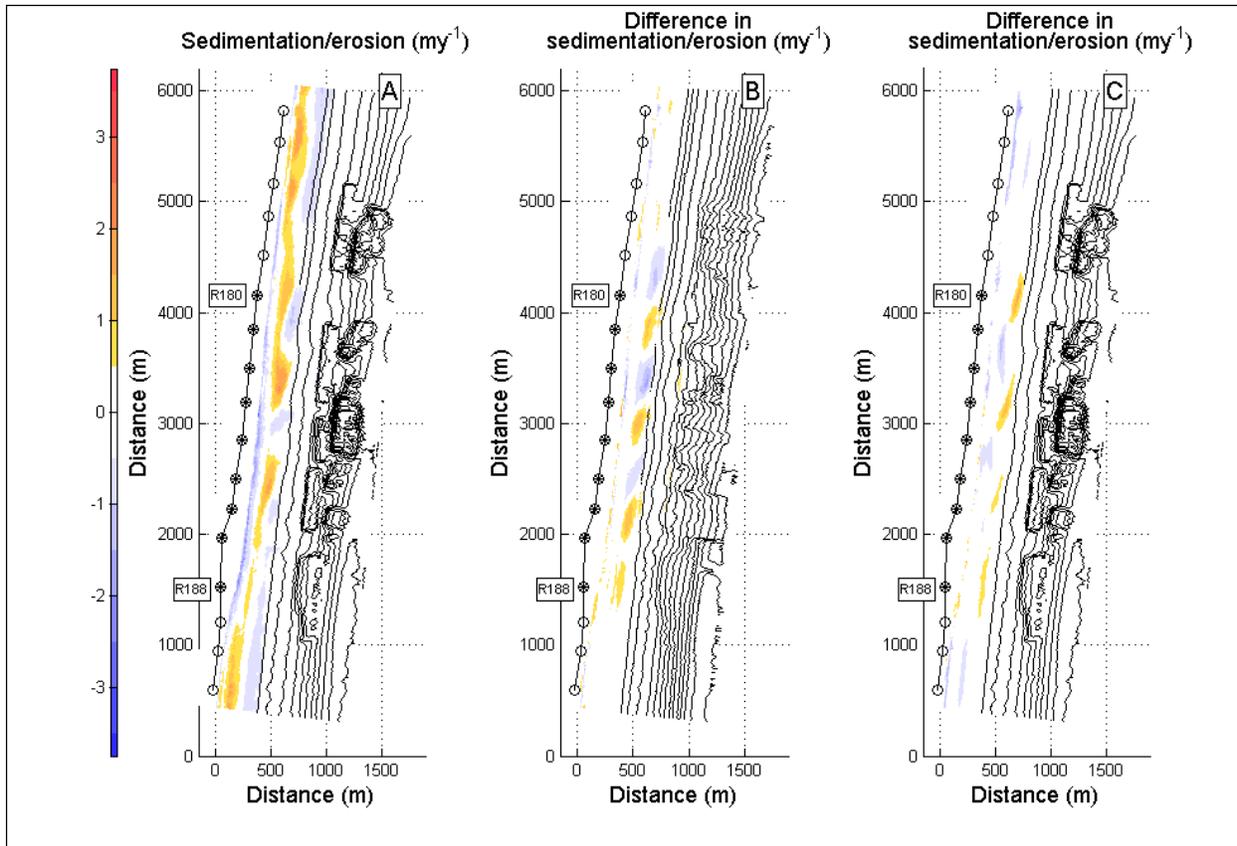


Figure 3.12. Comparison between sedimentation and erosion patterns. In (A) the sedimentation and erosion for a simulation with an averaged morphologic year simulated with 6 wave conditions, which were based on the 14 wave conditions derived from available hindcast wave data. Visible in red is the sedimentation and in blue the erosion. In (B) and (C) the difference between simulations with the original bathymetry and averaged wave climate (results in (A)) and respectively a simulation with a bathymetry without borrow pits (B) and the 1999 wave climate is given (C). The fill area is identified by solid dots.

A difference between model and measurements is the large fluctuations in sedimentation and erosion throughout the fill area which is caused by wave refraction over the borrow pits. A comparison between sediment transport magnitudes and wave height patterns alongshore showed that, although faster current velocities occur in the area of lower waves, the higher waves cause more sediment stirring, inducing higher sediment transport. The stirring up of the sediment by high waves contributes relatively more to sediment transport than high flow velocities.

Most sedimentation visible in Figure 3.12 (*e.g.* offshore of R-182) occurs below the MLLW line (NVGD -0.47 m), suggesting that sedimentation bars are formed in the surf zone leeward of the borrow pits. When comparing model results with beach profile data it was observed that large sedimentation in the surf zone in the form of bar growth is predicted and measured in profile R-182, but hardly any sedimentation is predicted, while measured, in the offshore bar of profile of R-184. Both profiles are situated on the leeward side of deep borrow pits (predominate wave angle NE), a small change in predominate wave angle could lead to sedimentation skewed more towards the north or south of the locations calculated by the model. Higher density data is required to analyze the surf zone sedimentation patterns (beach profiles are spaced about 300 m apart) as comparing model results with beach profile measurements showed that beach volume changes behind the borrows are overestimated.

3.6.3. Influence of the borrow pits on the morphologic changes

Differences between results of one year morphology simulations with and without borrow pits are shown in Figure 3.12B. Yellow areas in this figure do not necessarily indicate accretion and blue areas not necessarily erosion because the figure is a change analysis where results for the situation without borrow pits are subtracted from the results of the simulation with the borrow pits. The negative bed changes observed offshore of DNR monument R-182 in Figure 3.12B indicate that, compared to the bathymetry with borrow pits, less accretion in this area is observed. Figure 3.12B indicates that there is less alongshore variability in erosion and sedimentation trends when the bathymetry without borrow pits is used in the model. This is also indicated by the results in Table 3.3, which show that the standard deviation of the volume changes in the fill area for the simulation without borrow pits (#2) is less than half of the standard deviation for the simulation with original bathymetry (#1).

Table 3.3 Volume changes and the standard deviation for the six different simulations performed. A deviation is made between the fill (R-180 - R-188) and the study (R-175 - R-191).

Scenario	ΔV fill area (m^3m^{-1})	SD fill area (m^3m^{-1})	ΔV study area (m^3m^{-1})	SD study area (m^3m^{-1})
1. Original settings	-53.5	91.8	-42.9	77.7
2. Bathymetry without borrows	-39.7	41.5	-37.5	44.5
3. Bathymetry with uniform shoreline	-48.5	106.3	-40	98.3
4. Bathymetry with uniform shoreline and without borrows	-37.7	22.2	-41.5	27.1
5. Original bathymetry, 1999 wave climate	-37.1	85.3	-36.3	69.7
6. Original bathymetry, changed sequence wave climate	-41.1	51.8	-32	53.1

3.6.4. Influence of the shoreline orientation on morphologic changes

The shoreline orientation of the fill area is mostly a function of nourishment design. Shoreline orientation influences the velocity of the alongshore current and magnitude of the sediment transport and is thus expected to have a significant effect on beach morphology changes. The simulation with the original offshore bathymetry and uniform shoreline (#3 in Table 3.3), compared to the original settings (#1), shows a small increase in the standard deviation of the volume changes ($106.3 m^3m^{-1}$ vs. $91.8 m^3m^{-1}$) and a small decrease in the volume loss ($53.5 m^3m^{-1}$ vs $48.5 m^3m^{-1}$). Simulations without borrow pits but with the original shoreline orientation (#2) compared with simulations without borrow pits and with a uniform (straight) shoreline (#4) show that in the latter case the standard deviation decreases significantly ($41.5 m^3m^{-1}$ vs. $22.2 m^3m^{-1}$)

and total volume losses decrease slightly. This indicates that in addition to the borrow pits, shoreline orientation also plays a significant role in alongshore variability of beach morphodynamic response within the fill area.

Despite the fact that hydrodynamic simulations suggested a separation between the two phenomena (*viz.* the alongshore variation over the total fill length due to borrow pits and local higher erosion near the south due to shoreline orientation), the morphologic analysis shows that variations in volume changes over the total length of the fill are due to a combination of both phenomena. In other words, a separation between borrow area and shoreline orientation effects was not evident in the results of the current morphological simulations and further morphological change studies are recommended.

3.6.5. Influence of the wave climate on the morphologic changes

The sensitivity of the sequence of wave conditions was tested to investigate model sensibility to this parameter. Previous studies have shown that changing the order of wave conditions shows little to no influence on results from morphological simulations (*e.g.* Van Duin, 2002). In Table 3.3 results for both sequences are listed (#1 vs. #6), a significant difference in standard deviation and total volume loss between simulations that used two different sequences of wave conditions is observed. The distinction between the two is a reduced total volume loss, and a reduction in the fill variation alongshore; the different sequence (#6) has a standard deviation over the study area of $51.8 \text{ m}^3\text{m}^{-1}$ vs. $91.8 \text{ m}^3\text{m}^{-1}$ with the original sequence (#1). This indicates influence of the sequence of wave conditions. In order to evaluate further the influence of the wave climate, simulations with a different wave climate (conditions derived from statistical analysis for one specific year (1999)) were performed. The difference between simulations with the 1999 wave climate and the base simulation (#1) is shown in Figure 3.12C and listed in Table 3.3. The standard deviation for the fill area (indication of the variation) is nearly the same (#1 and #5): $91.8 \text{ m}^3\text{m}^{-1}$ vs. $85.3 \text{ m}^3\text{m}^{-1}$. However, there is a deviation between the location of sedimentation and erosion between the two simulations. This indicates a large variation in morphodynamic response in the model due to changes in the wave schematization and emphasizes the importance of the selection of the wave conditions in predicting the beach nourishment behavior in the study area.

3.7. EFFECTS OF WAVE DIFFRACTION AND INITIAL BATHYMETRIC CONDITIONS ON MODEL PERFORMANCE

Originally, Hartog *et al.* (2008) indicated that possible improvements to the model setup discussed in previous sections of this chapter should concentrate at addressing the model underestimation of the magnitude of erosion in the erosional hot spot (segment between R-186 – R-187). It was then hypothesized that the underestimation of hot spot erosion could be due to the fact that the model simulated currents in a 2DH-depth averaged mode, the annual wave climate developed may have been too mild or incurred direction biases, the absence of diffraction in the current version of SWAN, or differences between model initial conditions and monitoring data initial conditions. The latter refers to the fact that the model results presented in previous sections of this chapter used the nourishment bathymetry measured after the 2002 beach fill obtained from laser airborne survey measurements conducted in October, 2002 while the initial condition for the measured calibration dataset was a beach profile survey conducted in December 1992, after the construction

of the 1992 beach nourishment. Hartog *et al.* (2008) also raised the hypothesis that the lack of diffraction in the wave model may have also caused an overestimation of borrow area impacts on waves, which led to predictions of larger alongshore variability in beach volume changes than measured.

Benedet *et al.* (2006) investigated some of these hypothesis, specifically these authors evaluated the effects of the inclusion of wave diffraction in an updated version of SWAN (version 40.41) and improvement in the representation of model initial conditions in the performance of morphological model predictions and the results are summarized the in the following sections of this chapter.

3.7.1 Beach Volume Change Measurements Used in Model Comparisons

The 1992 beach nourishment project was constructed along 3 km of beach between monuments R180 and R188 (Figure 3.13) with about 940,000 m³ of sand (313 m³/m). Most of the fill volume was placed on areas that showed greater erosion since the last renourishment. Offshore features that may influence project performance include dredged borrow areas, and shore parallel reefs (Figure 3.13). Quasi-circular deep borrows areas in figure 1 were dredged in the 1970s and early 1980s while the rectangular shallower cuts were dredged in the 1990s and in 2002.

Computations of beach volume changes following the 1992 nourishment were based on data from annual beach profile surveys. Volume changes were calculated from the monument location (generally on the back of the dune) to the -7.5 m depth contour which is the offshore limit of most surveys and the estimated closure depth of the study area (CPE, 2001). Previous work by the authors (Benedet *et al.*, 2007) indicated that most of the beach fill eroded during the first two years post-construction and volume losses were reduced in subsequent years. Numerical modeling reported in this section aims at reproducing the beach volume changes observed during these two initial years. Volumetric changes described hereinafter refer to this time period (Dec-92 to Dec-94).

Erosion was observed over the fill area (between monuments 180 and 188) and beaches to the north and south of the fill were either stable or accretion. The fill response can be divided into three main segments, (1) An area with intermediate erosion (average of change of -67 m³/m/yr) between monuments 181 and 183, an area with milder erosion between monuments 184 and 185 (average change of -29 m³/m/yr) and an area with higher erosion between monuments 186 and 188 (average change of -96 m³/m/yr). The average volumetric change over the entire beach fill (between monuments 180 and 188) was -62 m³/m/yr for the two-year period. Total volumetric changes were estimated by multiplying the unit volume change by the distance between profile monuments. Total volume loss over the fill area over the two year period was approximately 152,000 m³. More than half of the erosion occurred in the area between profile 186 and 187.

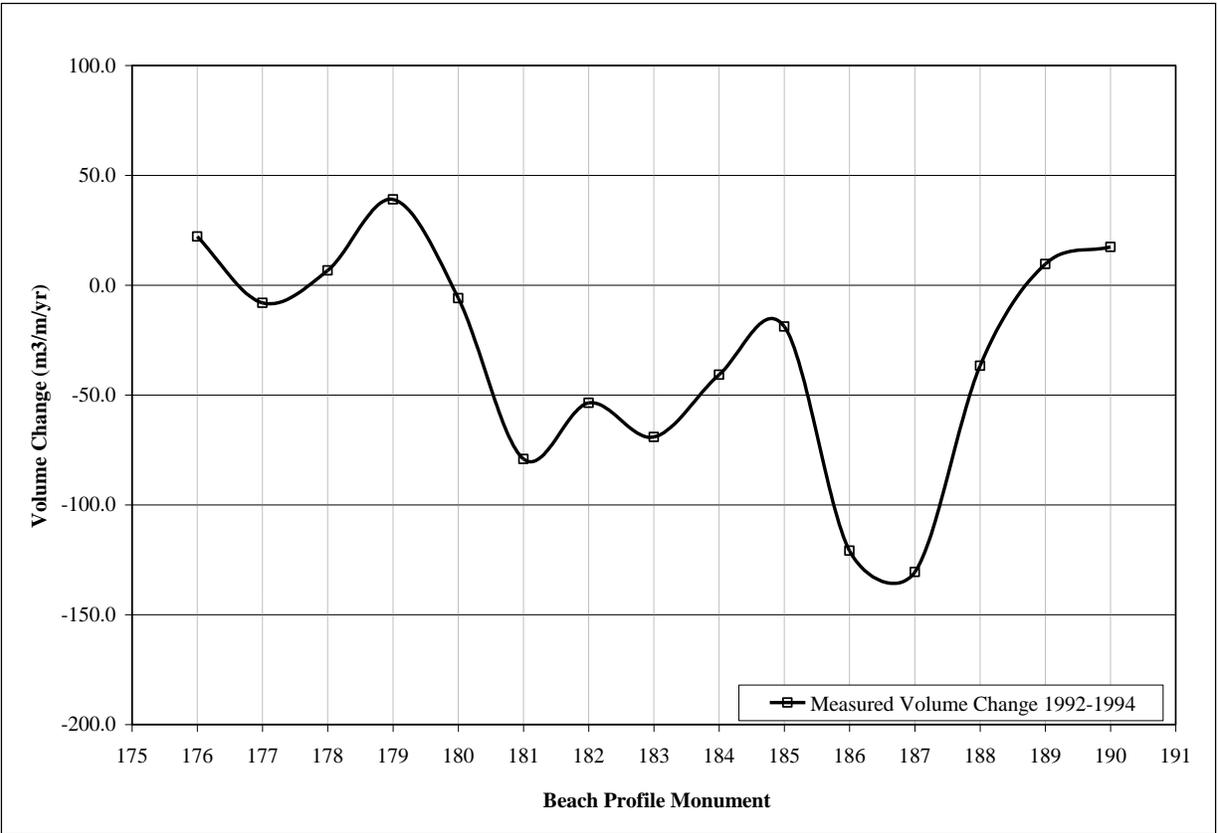


Figure 3.13. Volume changes measured between December 1992 and December 1994. The beach is bounded by monuments 180 to the north and 188 to the south.

3.7.2 Effects of Wave Diffraction on Model Predictions

Preliminary model efforts by the authors were found to overestimate beach changes behind the borrow sites. Significantly higher than observed erosion was simulated at profile 178 on the edge of a deep-cut borrow area dredged in 1973, higher than observed deposition was simulated at profiles 182 and 183 behind the 1978 and 1973 deep borrows, followed by higher erosion at profile 184 on the southern edge of the deep borrows dredged in 1973-1984 (see Figure 3.1 for dredge pit locations and Figure 3.14 for predicted versus observed beach volume changes).

Hartog *et al.* (2008) hypothesized that the absence of wave diffraction in SWAN was one of the reasons for the over-estimation of beach changes behind the borrow areas. Information available in the literature (Bender and Dean, 2003) also suggested that wave diffraction processes are important for the evaluation of borrow area impacts on beaches.

SWAN results without diffraction showed abrupt wave focusing and wave shadows within the project area, especially behind the deeper borrows dredged in the 1970s. Wave heights just before breaking simulated by Hartog *et al.* (2008) shown here in Figure 3.8 varied +/- 1 m alongshore for waves with an input boundary height of 2 meters (11 s T_p , 67° wave direction and 8° degrees directional spreading). It was suggested by these authors that, with the implementation of wave diffraction, gradients in wave heights alongshore would be smoothed out as wave energy spreads

laterally from the high wave areas at the borrow edges to the shelter zones behind the borrows. This process could in turn reduce the magnitude of beach changes behind the borrow sites predicted by the model.

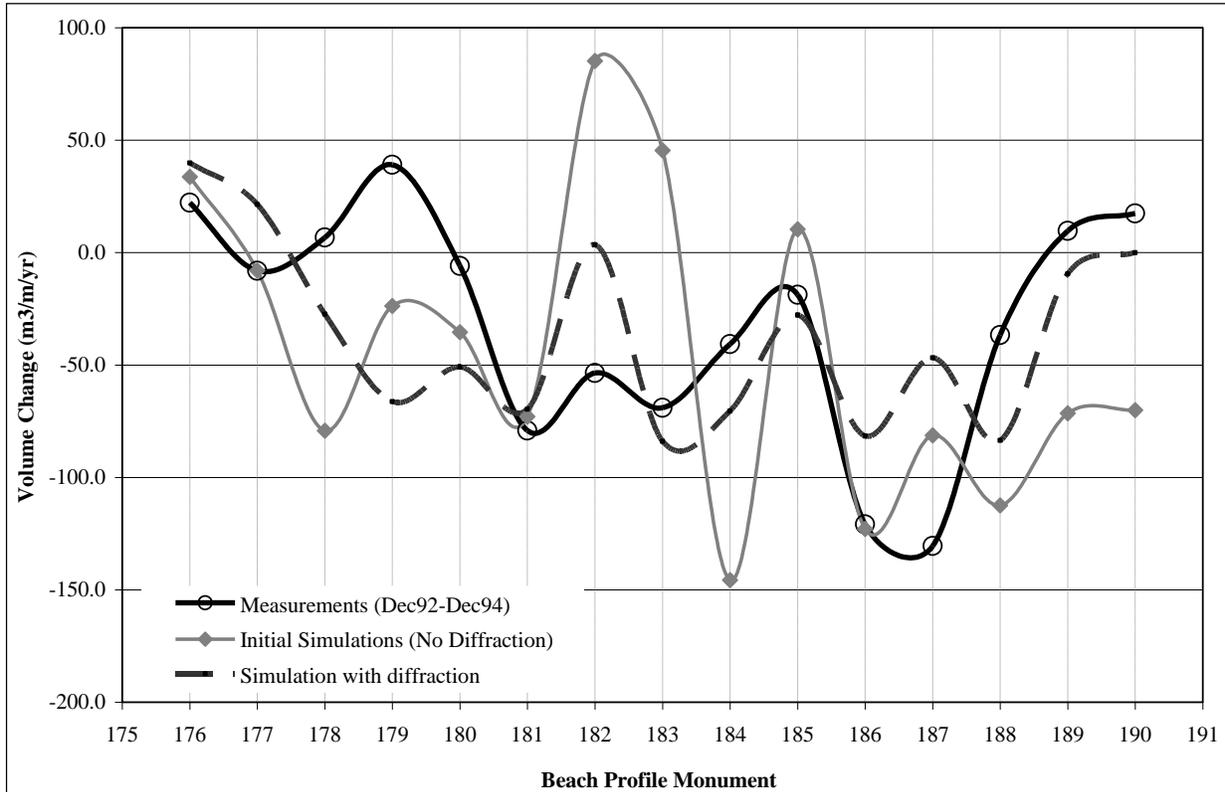


Figure 3.14 Comparison between measured and predicted beach volume changes. Results for Delft3D annual simulations with and without diffraction are shown.

The effects of diffraction can be partially simulated in SWAN or other spectral wave models by applying a wider directional spreading to the incident wave spectra or, more recently (SWAN version 40.41, Holthuijsen *et al.*, 2003) it can be modeled explicitly in SWAN. Since the waves that most influence the sediment transport in the project area are northeast swell waves, a relatively narrow direction spreading was used. Diffraction was modeled using the phase-decoupled approach of Holthuijsen *et al.*, 2003 available in SWAN 40.41. A comparison of nearshore wave heights is shown in Figure 3.15, the left plot (“A”) shows a simulation without diffraction activated while the right plot (“B”) shows a simulation with diffraction. The simulation used the following boundary conditions: H_{sig} of 2 meters, $11.5 T_p$, 60° wave direction and, 8° directional spreading, Jonswap spectra with 3.3 peak enhancement factor. It is noticed that the wave focusing zones diminished significantly in size and magnitude in the simulations with diffraction, especially at profiles 182 and 183 (right plot, Figure 3.15). The large shelter zone at monument R182 simulated without diffraction (see left plot, Figure 3.15) was smoothed out in the simulation with diffraction (see right plot, Figure 3.15). Wave focusing zones at profiles 186 and 197 were also diminished in the simulations with diffraction (right plot, Figure 3.15).

SWAN 40.41, with diffraction activated, was run for the annual wave climate coupled with Delft3D-Flow to simulate flows, sediment transport and annual beach volume changes. Results comparing the annual beach volume change observations to predictions using SWAN with and without diffraction, are shown in Figure 3.14. Simulations with diffraction showed some improvements in the model results, *viz.* the erosion at monument 178 was slightly reduced, the deposition at profiles 182 and 183 were greatly reduced and the erosion at profile 184 was also reduced to magnitudes similar to the measurements (Figure 3.14). The formation of a submerged salient in the shadow zone behind the borrow areas as suggested by Hartog *et al.* (*in press*) was not observed in the annual Delft3D runs with wave diffraction processes included. The downside of the results from the annual simulation with diffraction is that the erosion of the hot spot, located in the south end of the project, was also reduced. However, as a general trend, the implementation of diffraction improved model prediction and reduced overestimation of beach changes behind borrows sites at monuments R182 and R183 (Figure 3.14).

3.7.4. Effects of Initial Bathymetric Conditions

Simulations with wave diffraction included in SWAN partially addressed the overestimation of beach changes behind borrow areas observed by Hartog *et al.* (2008) and discussed in previous sections of this chapter. But even after this improvement, significant deviations between predicted and observed beach volume changes persisted (see Figure 3.15). Even though there are many simplifications necessary to conduct long-term (annual to decadal time-frames) morphological modeling, model predictions can be greatly improved by using a realistic representation of initial conditions coupled with representative forcing at the model boundaries.

For optimal results, initial bathymetric conditions in the model should preferably be concurrent with the initial conditions of the calibration dataset. Smit (2010), for example, observed that initial morphological conditions are many times even more important than hydrodynamic forcing in determining the morphological evolution of a specific beach. The previous modeling results showed here (*i.e.* Figure 3.15) used a bathymetric dataset collected October 2002, 6 months after the 2002 beach nourishment. The calibration dataset, on the other hand, was obtained after the 1992 beach fill (Dec-92 to Dec-94). Differences between the initial conditions of the calibration dataset and the model may cause deviations between model predictions and beach volume change observations. Essential differences between these two datasets (model and calibration) that may influence model prediction accuracy include: (1) three additional borrow areas were dredged in 2002, which were not present in the time period the calibration data was measured, (2) the bathymetric survey used as model input was obtained six months after a nourishment project, enough time for initial fill equilibration processes to modify beach configuration, while the calibration dataset was measured immediately after fill construction and (3) even though the 2002 beach nourishment project had similar dimensions than the 1992 project, differences in fill distribution are expected to occur.

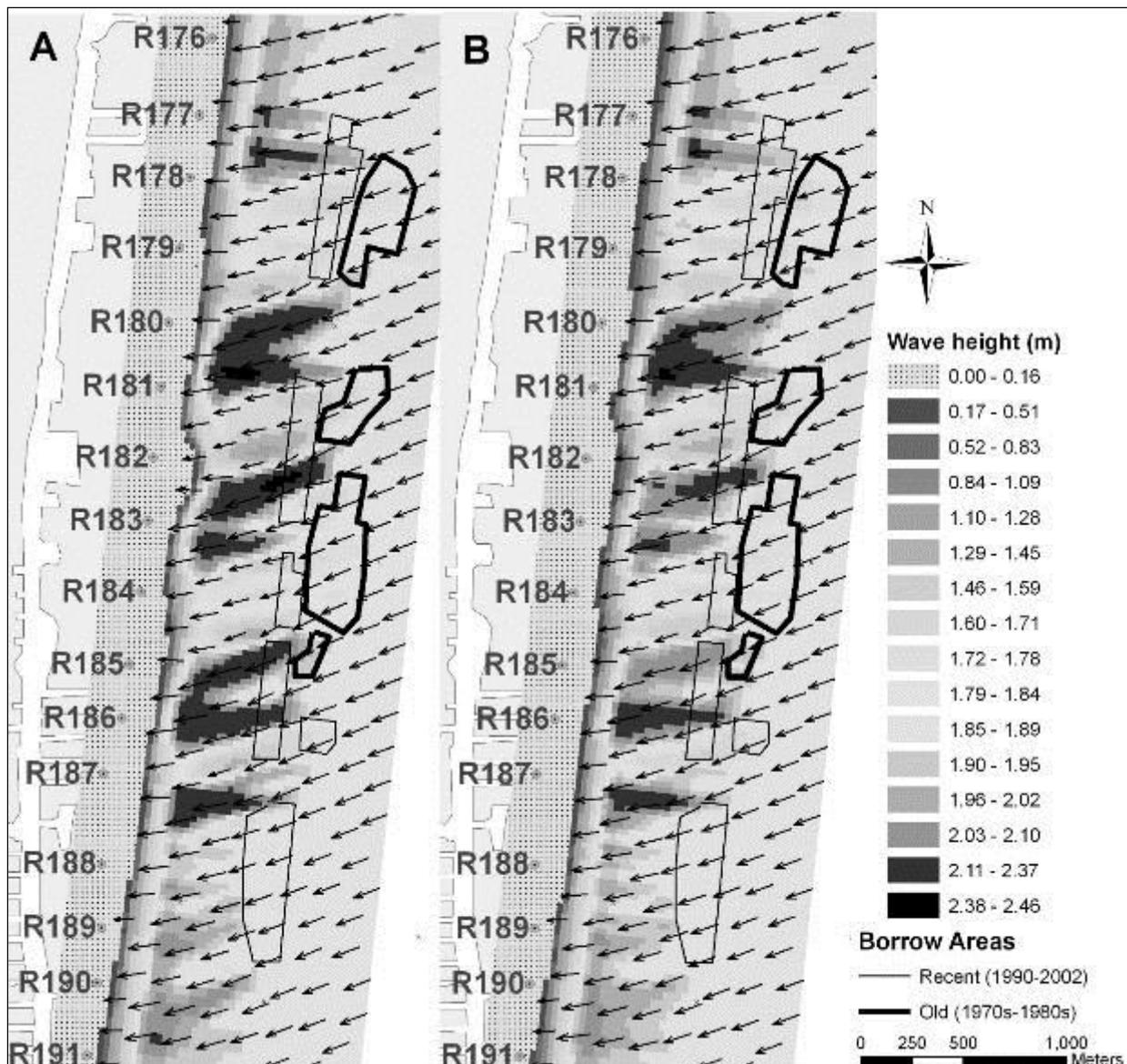


Figure 3.15. Comparison of two SWAN simulations, one without wave diffraction (left plot, A) and with diffraction (right plot, B).

To improve the representation of initial conditions in the model, modifications to the input bathymetry were performed. First, the borrow areas dredged in 2002 were removed mathematically (filled) from the bathymetry dataset to represent pre-dredging conditions, similar to those of December 1992. Second, laser airborne bathymetry data from the nearshore (subaerial beach to the -7.5 m beach contour) was replaced by the beach profile survey data measured immediately after construction of the 1992 beach nourishment. The post construction beach profile data were measured at profile stations spaced 300 m apart along the beach; this data was interpolated (triangular interpolation) to fill the model computational grid. The combined effects of the beach fill, together with the interpolation of widely-spaced profile data produced a smoothed surf-zone morphology with a prominent steep seaward excursion of the shoreline within the beach fill area.

These modifications to the model initial bathymetric conditions improved model predictions significantly as shown in Figure 3.16. Predictions of beach volume changes with diffraction included in SWAN, and improved model bathymetry showed similar trends as the measured data *viz.* two zones with higher erosion at the project extremities (R181-182, R186-187) and a zone with milder erosion in the center of the beach nourishment project (R184-85) (Figure 3.16). Deviations from model predictions and observations still occur, especially to the north of the beach fill project (R176 to R179). However, within the beach fill, the annual beach volume change simulation matched well the observations and total volume change predicted by the model lied within 10% of the measured volume change.

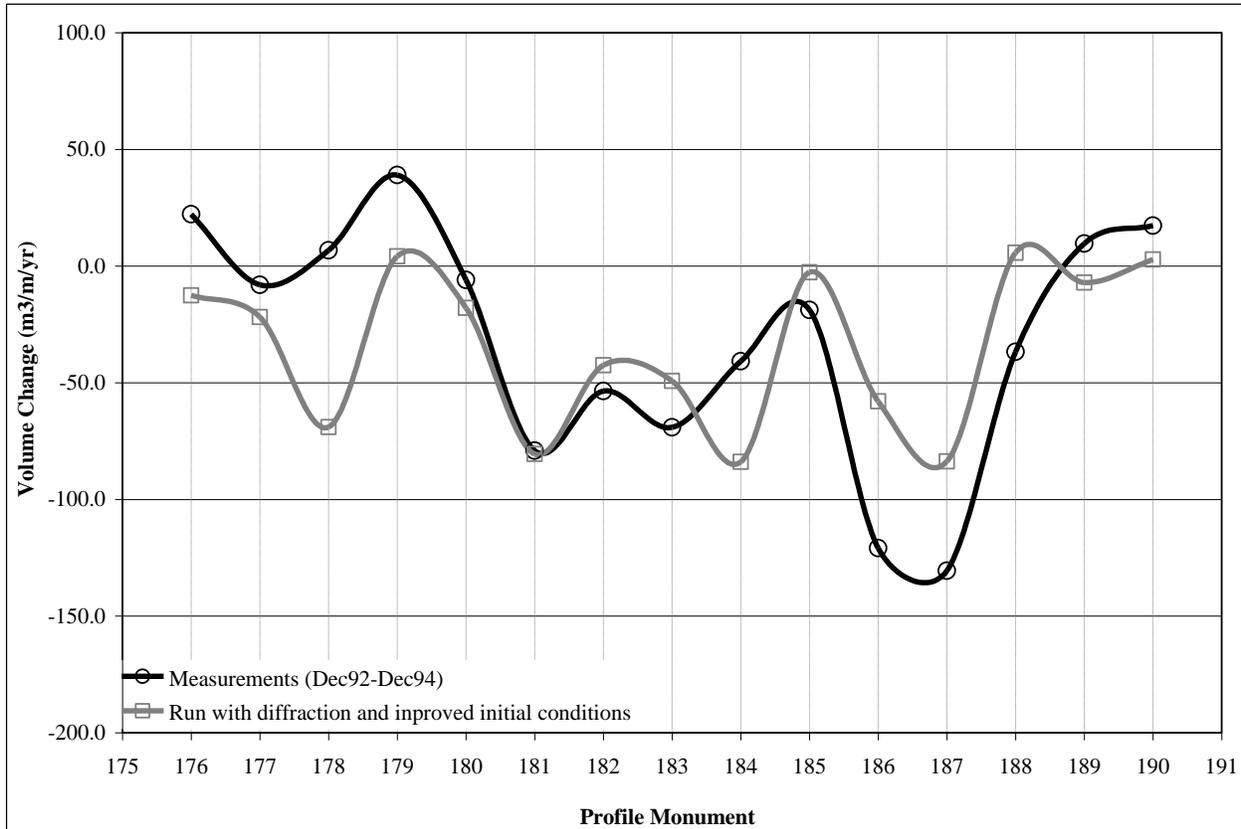


Figure 3.16. Comparison of annual Delft3D simulation with improved initial conditions versus observed beach volume changes.

Results indicated that inclusion of wave diffraction processes and improvements to the initial model conditions improved significantly the agreement between simulated and observed beach volume changes. Limitations of the phase-decoupled method include the fact that interactions between incident waves and reflected waves from structures are not included; however this limitation is not significant in this particular study area. Holthuijsen *et al.*, (2003) state that the phase-decoupled diffraction approximation in SWAN is more suitable for large scale applications in relatively open coasts with occasional structures, and should be not be used in areas where the distance between offshore obstacles and the shoreline is small (less than a few wavelengths) or in areas where wave reflection is significant. These limitations are not present in the example studied here and therefore the phase-decoupled option in SWAN can be used in our case study.

In addition to the implementation of wave diffraction, a better representation of initial bathymetric conditions (borrows and post-construction template) proved to be important for the fill volume change simulations.

Some deviations between beach fill volume change predictions and observations still persist. These may be attributed to a series of factors including the absence of concurrent wave and morphology measurements (a schematized wave climate using long term dataset was used), approximated representation of fill template by using widely-spaced beach profile data, grain size variations induced by fill construction methods and coastal processes that may not be properly represented by the simplified schematization of boundary conditions (waves, winds and tides) or limitation in our knowledge in surfzone processes.

3.8. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The Delft3D model proved to be an adequate tool for simulating beach volume changes in the project area, especially when model improvements (wave diffraction and initial bathymetric conditions) were implemented. The method of using different bathymetric scenarios in a process-based morphodynamic model proved to be a useful approach in identifying the different processes that influence fill performance and assessing its relative effects.

The wave transformation analysis demonstrated that the offshore shore parallel reefs influence on the nearshore wave climate is negligible (difference in simulated wave height was less than 5 %). The nearshore borrow pits, dredged for the nourishment of Delray Beach, on the other hand, influence nearshore waves climate significantly (fluctuations to 50 % of the input wave height are modelled). It can be observed from model results that the borrow pits influence the beach morphology changes significantly causing twice as large alongshore variation in sediment transport than simulations with bathymetric condition without borrow pits. The model results also show that the deeper and steeper borrow pits (dredged in 1973 and 1978 and as deep as 8 m below the seabed) have the larger influence on the waves (causing the fluctuations of 50% of boundary significant wave height), while the shallower (about 2 m below the seabed) and less steep borrow pits (dredged for nourishments since 1984) show less influence on nearshore waves (fluctuations in wave height are less than 5 %). This suggests that nearshore dredging is possible without significantly affecting the wave regime and that model results can be used to refine borrow area design to reduce impacts on the nearshore wave field.

In addition to the alongshore variation in wave height and wave direction induced by the borrow pits, the behavior of the beach nourishment project seems to be influenced by the shoreline orientation and annual variability in the wave climate. Although the hydrodynamic analysis suggested that the shoreline orientation at the south end of the fill area may cause the erosion hot spot in that location, morphological simulations were inconclusive in this matter, *i.e.* a separation between borrow area and shoreline orientation effects was not evident in the results from the current morphological runs. Further morphological change studies are recommended to provide enough basis for a differentiation of the relative contributions of these features (borrows and post construction template) on fill evolution in order to isolate the processes behind the higher erosion in hot spot areas, especially in the south end of the beach fill.

Improved predictions of beach nourishment volume change trends were obtained by using the most recent version of SWAN (40.41) with a phase-decoupled wave diffraction formulation and by improving the initial bathymetric condition in the model and improved initial bathymetric conditions. Sensitivity analysis of morphologic simulations also showed that a significant difference in standard deviation and total volume loss occurs when different sequences of wave conditions are prescribed in the model suggesting that the sequence of wave conditions feed into the model boundary, the number of wave cases and the method of wave climate schematization are also affecting model outcome. Therefore, more research in wave climate schematization and sequencing should also be conducted in order to improve model predications of beach volume change. Deviations between beach volume change predictions and observations will always occur, but tend to be diminished as more data becomes available and our knowledge of coastal processes, methods of schematizing boundary conditions and model formulations improve.

The observed alongshore variability of nourishment response should be investigated further as it may provide new insights into methods of designing and selecting borrow areas, determining the borrow area dimensions and developing more sophisticated ways of placing the fill on the beach.

The model setup described here will be improved in the following chapters of this thesis to investigate outstanding questions regarding fill performance and EHS controls at Delray Beach and provide guidance to engineering design optimization of beach fill and dredge pits.

CHAPTER 4. EVALUATION OF THE PHYSICAL PROCESS CONTROLLING BEACH CHANGES ADJACENT TO NEARSHORE DREDGE PITS

Abstract

Numerical modeling of a beach nourishment project is conducted to enable a detailed evaluation of the processes associated with the effects of nearshore dredge pits on nourishment evolution and formation of erosion hot spots. A process-based numerical model, Delft3D, is used for this purpose. The analysis is based on the modification of existing bathymetry to simulate “what if” scenarios with/without the bathymetric features of interest. Borrow pits dredged about 30 years ago to provide sand for the nourishment project have a significant influence on project performance and formation of erosional hot spots. It was found that the main processes controlling beach response to these offshore bathymetric features were feedbacks between wave forces (roller force or alongshore component of the radiation stress), pressure gradients due to differentials in wave set-up/set-down and bed shear stress. Modeling results also indicated that backfilling of selected borrow sites showed a net positive effect within the beach fill limits and caused a reduction in the magnitude of hot spot erosion.

This chapter is based on the following publication:

Benedet, L., and List, J.H., 2008. Evaluation of the Physical Process Controlling Beach Changes Adjacent to Nearshore Dredge Pits. Coastal Engineering, 55 (2008) 1224–1236.

4.1. INTRODUCTION

Beach nourishment is commonly conducted to mitigate for coastal erosion. The evolution of beach nourishment projects has been studied by many in recent years. NRC (1995), USACE (2002) and Dean (2002), summarize most of the recent work on the topic with emphasis on design practices used in the North America. Various articles published in a special issue of Coastal Engineering edited by Hamm and Stive (2002) and Hamm et al. (2002) offer a comprehensive review of beach nourishment practices in Europe. The consensus is that a range of factors can influence beach nourishment evolution, these include offshore bathymetry, wave climate, magnitude of sediment transport, project dimensions (length-width), sediment compatibility between sand mining site and native beach, amount of sand placed on the beach (volume per unit length), construction methods and fill placement location. The effects of these parameters can be evaluated using a range of methodologies that range from analytical formulations derived from observations (data-based statistical models) and process-based numerical models (physics-based models).

Of particular interest is the development of areas within beach fills that erode much faster than the nourishment average. These areas are commonly defined as Erosion Hot Spots (EHS). EHS are important because many times they dictate the renourishment volumetric requirements of a project (NRC, 1995). Due to its significance to the applied coastal engineering field, EHS have received considerable attention over the last decade.

Kraus and Galgano (2001) investigated hot spots causes and time-frames and classified 18 types of EHS. Benedet et al. (2007) investigated erosion hot spots at a nourishment project in Delray Beach, FL. and defined an EHS as: “An erosional hot spot is an area within a beach nourishment project that erodes at least two times more than the nourishment average and can be quantified comparing the volume loss (m^3m^{-1}) or shoreline retreat (myr^{-1}) of a specific beach segment with the average volume loss of the entire nourished area”. The definition of Benedet et al. (2007) is used in this manuscript when referring to EHS.

If causes of erosion hot spots can be properly identified, measures can be taken to reduce the severity of erosion at these areas. A common practice in the U.S. is to overfill hot spots areas to compensate for the additional erosion observed at these zones (i.e. NRC, 1995, CPE, 2001, Dean, 2002). Coastal structures such as detached breakwaters, submerged reefs or groins may also be used to counteract hot spot erosion. Campbell and Jenkins (2001), for example, proposed a methodology to selectively place coastal structures within a beach nourishment project to reduce long-term hot spot losses.

A proper understanding of the physical processes controlling EHS development can provide the basis for the rational design of appropriate erosion mitigation measures. Recent developments of process-based modeling allow for detailed investigation of physical processes controlling coastal behavior (Lesser et al., 2004, List et al., 2006). Benedet et al. (2006, 2007) and Hartog et al. (in press) utilized process-based modeling (Delft3D) to investigate processes controlling alongshore variability in Beach Nourishment Performance at Delray Beach. The work presented in this paper is a follow up on previous research conducted by Benedet et al. 2006, 2007, Hartog et al., in press with emphasis given to the identification of physical processes behind the effects of bathymetric features such as dredged borrow sites on beach erosion and deposition patterns and the development of EHS. Potential mitigation measures that could be implemented to reduce EHS losses are also discussed.

4.2. STUDY AREA

The study area, Delray Beach, is located on the southeast coast of Florida (Figure 4.1), about 80 km north of Miami Beach. Beach profile monuments established along the beach at approximately 300 m intervals are used as a geographic reference for different fill segments. Locations of the beach profile monuments (profile markers or staffs) are indicated in Figure 1. The profiles are used to assess beach volume change on an annual basis as part of a continuous beach monitoring program sponsored by the city of Delray Beach. The Delray Beach Nourishment Project is located between profile monument R180 to the north and R188 to the south.

Delray Beach is located on the Florida Peninsula, a large carbonate platform containing a thick sedimentary sequence that was constructed generally from the Jurassic to the Miocene (viz. from about 180 to 5 million years ago) (Davis, 1997). The shelf is dominated by sandy sediments and hard substrates made of sandstones and coquina of the carbonate platform, Anastasia Formation and modern coral reefs (Finkl et al., 2003). When eroded, these hard substrates produce sand and gravel sized fragments of carbonate sand. These carbonate sediments are commonly washed up on beaches mixing with siliciclastic sediments transported from the northeast to form the observed suite of beach sediments (Hine et al., 1998). Barrier coral reef systems lie about 1 km offshore from the project area, at depths of 18 to 22 m. These reefs comprise the northern-most extension of the Florida Reef Tract (Lidz et al., 1985). Additional reef tracts occur farther offshore at greater depths. Sedimentary troughs located between the beach and the offshore coral reefs are infilled with sandy sediments that have been used as borrow materials for the Delray Beach nourishment projects (Benedet et al., 2007).

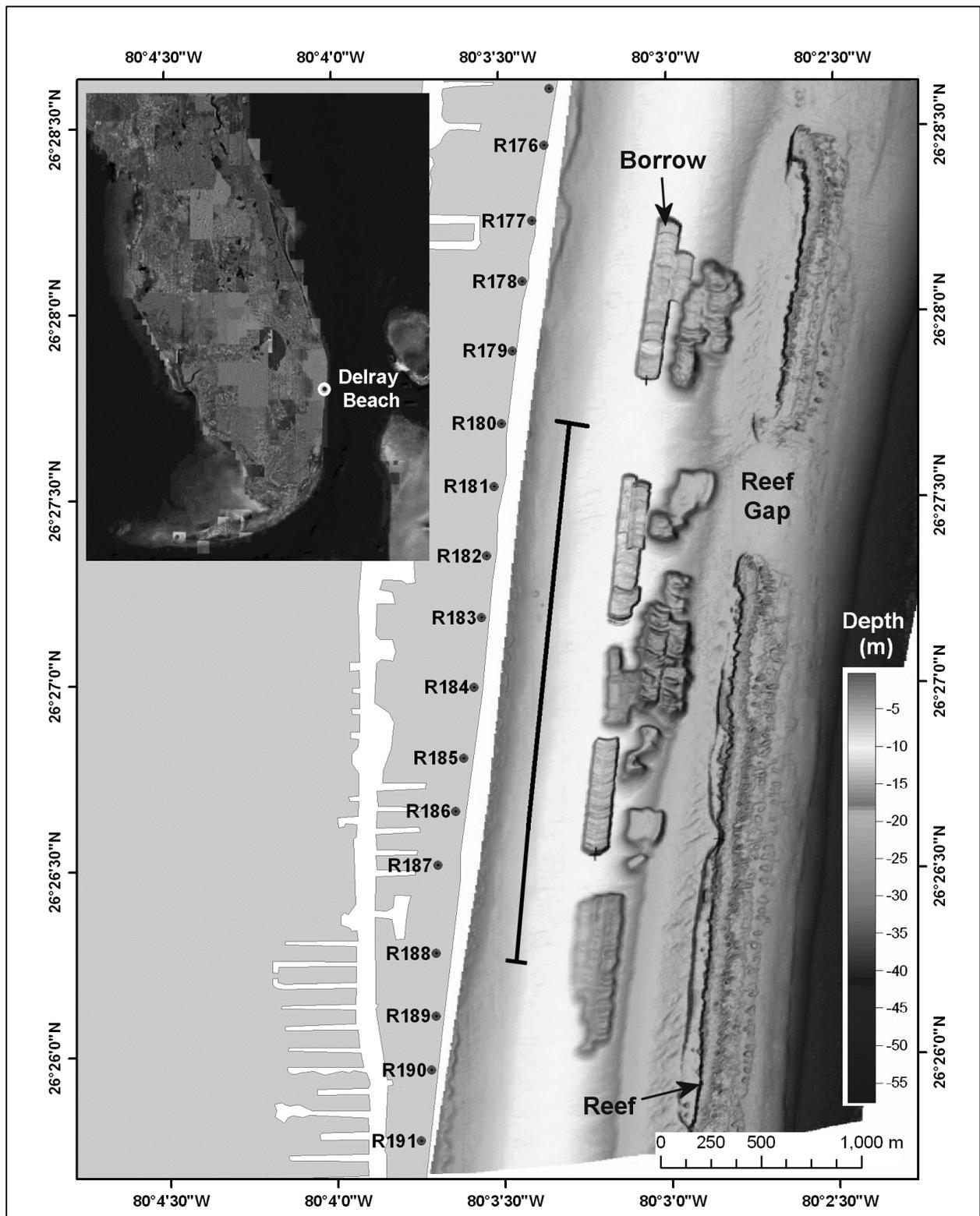


Figure 4.1 Study area location diagram showing beach profile monuments used as a geographical location in this manuscript.

4.2.1. Beach Nourishment History and Previous Studies

Previous research about the Delray Beach nourishment project pertinent to this study include: Beachler, (1993), Fernandez (1999), Gravens (1997), CPE (1994, 1995, 1996, 1998, 1999 and 2001), Hartog (2006), Benedet et al. (2006, 2007) and Hartog et al. (in press).

Delray Beach was initially nourished in July 1973 with the placement of 1,250,000 m³ of sand. It was subsequently renourished in 1978, 1984, 1992 and 2002. Recent studies (Benedet et al., 2007, Hartog, 2006) indicate that volume changes from the project site vary greatly alongshore and that an area located in the southern end of the nourishment project (profile monuments R186, R187) is an erosion hot spot. About 50% of total erosion losses from the project area occurs within this EHS. Higher erosion rates in this EHS segment are persistent in time occurring throughout the entire post-construction lifetime. The EHS zone extends for approximately 600 m alongshore.

Numerical modeling conducted by Benedet et al. (2007) and Hartog (2006) suggests that offshore bathymetric features and changes in shoreline orientation are responsible for large alongshore variability of erosion rates within the project area. A quantification and characterization of the hot spots observed after the construction of the 1992 beach nourishment project was conducted by Benedet et al. (2007). The most severe EHS identified by these authors (R186-R187) coincided with the location of EHS previously identified by the studies of Fernandez (1999) and CPE (2001). Benedet et al. (2007), based on an analysis of wave and flow model results, suggests that the EHS located at R186 and R187 may be caused by changes in shoreline orientation that result from the beach fill construction.

The relative effects of nearshore reefs and borrow areas on this nourishment project were studied by Hartog et al. (in press). These authors show that the nearshore reefs that occur offshore of the project area (see figure 4.1) have limited effect on beach nourishment performance, but that dredged borrow pits exerted a clear influence on beach changes. The deeper borrow areas dredged in the 1970s and 1980s were singled out as the main drivers of alongshore variability in fill erosion rates. Hartog et al. (in press) was able to predict total volumetric loss from the project area using Delft3D, however beach changes behind borrow areas were overestimated by these authors. It was hypothesized by these authors that overestimation of beach changes behind borrows could possibly be attributed to the fact that the version of the wave model used at the time (SWAN version no 40.31) did not account for the effects. It was also suggested that differences between model predictions and beach volume change observations could be due to differences in the initial conditions (bathymetry) used in the model and the calibration dataset. The input bathymetry used by these authors was derived from laser airborne survey measurements conducted in October, 2002 while the initial condition from the calibration dataset was a beach profile survey conducted in December 1992, after the construction of the 1992 beach nourishment.

The effects of wave diffraction and initial bathymetric condition on Delft3D beach volume change predictions were evaluated by Benedet et al. (2007). These authors confirmed earlier speculation that the model was over-predicting beach changes behind the borrow sites because of the absence of wave diffraction (Hartog et al., in press). The observation that wave diffraction is an important parameter to consider when evaluating borrow area impacts on nearshore waves and wave-driven flows and sediment transport is also supported with earlier work on borrow area effects on nearshore waves (i.e. Bender and Dean, 2003). By adding wave diffraction and improving initial bathymetric conditions of the model presented by Hartog *et al.* (2008), Benedet

et al. (2007) were able to satisfactorily predict volume changes of the Delray Beach 1992 beach nourishment project, with noticeable improved accuracy behind the borrow sites (Figure 4.2). Results of Benedet et al. (2006) set the framework for additional research on the influence of the borrow pits on EHS formation.

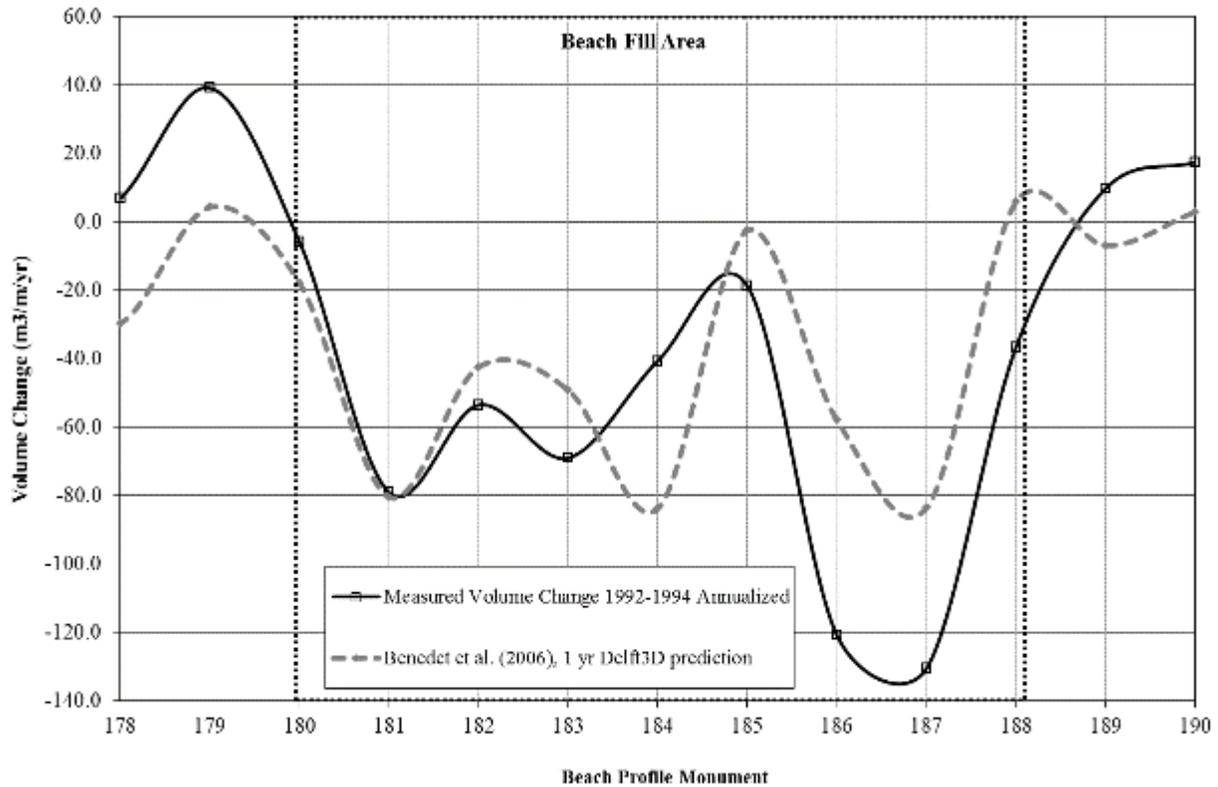


Figure 4.2. Comparison of annual Delft3D simulation with improved initial conditions versus observed beach volume changes between December 1994 and December 1994.

4.3. NUMERICAL MODEL SETUP

Delft3D, a process-based model containing several modules for the simulation of wave transformation, nearshore currents, sediment transport, and morphology change, was used in this work. Delft3D-WAVE uses SWAN (Holthuijsen et al., 1989, Booji et al., 1999). Flow calculations used Delft3D-FLOW (Lesser et al. 2004) and were conducted in 2DH (depth-averaged mode) because the main objective of the study is to evaluate alongshore variations in flow response (where 2DH processes predominate), with little to no emphasis on cross-shore processes (where 3D processes would be more relevant).

In this work the model setup (grids, boundary conditions and model parameters) is similar to the used in Benedet et al. (2007), who were able to satisfactorily replicate observed beach changes (Figure 4.2).

4.3.1. Model Grids and Bathymetry

This study used two main model domains. The first domain contains the real dimensions of Delray Beach and uses local measured bathymetry. The second domain uses a schematized bathymetry to isolate a particular bathymetric impact, a deep borrow pit situated offshore of the Delray Beach project. For the first domain (the one contained the real dimensions of Delray Beach), three different nested grids were used. A large regional grid (SWAN-regional) with varying cell spacing from 100 x 100 m to 250 x 250 m was used to transform waves from deepwater to the area of interest. A detailed nearshore grid (SWAN-nearshore), with varying grid cell spacing, was nested inside the regional grid in the area of interest to calculate wave transformation and wave-induced radiation stresses. The grid was refined to cells of 25 x 25 m within the project area and grid cells smoothly coarsened to a maximum of 75 m by 75 m towards the boundaries. The hydrodynamic and morphology calculations were conducted on a smaller grid nested inside the SWAN-nearshore grid. The grid used for these simulations is finer in the area of interest with cells from 10 x 10 m near the area of interest to 30 x 30 m towards the boundaries. Cross-shore processes are taken into account, but approximated with the depth-averaged calculations. Setup of the schematic model followed an approach similar to the case study and is briefly described in the schematic model section, presented separately in this manuscript.

LADS (Laser Airborne Depth Sounder) bathymetric data measured in October, 2002 were used as input data for bed elevation (Figure 1) outside of the surf zone to the offshore limits of the DELFT3D flow grid. This dataset includes additional borrow sites, dredged in early 2002, that were not present during the time period when the beach volume change measurements (used for calibration purposes) were conducted (Dec-92 to Dec-94).

Measured beach volume changes used for comparison with model results were collected after the 1992 beach nourishment, while the available bathymetry data used in the model was collected in October 2002. Consequently some adjustments of the bathymetry were implemented to permit a realistic representation of the beach nourishment after the construction of the 1992 beach fill (see also BENEDET *et al.*, 2006). First, the borrow areas dredged in 2002 (which were not present after the 1992 beach fill) were removed mathematically (filled) from the LADS bathymetry dataset conditions similar to those of December 1992. Second, laser airborne bathymetry data from the nearshore and surfzone (subaerial beach to the -7.5 m beach contour) was replaced by the beach profile survey data measured after construction of the 1992 beach nourishment. The post construction beach profile data were measured at profile stations spaced 300 m apart along the beach; these data were interpolated (triangular interpolation) to fill the model computational grids. The combined effects of the beach fill, together with the interpolation of widely-spaced profile data produced smoothed surf-zone morphology with a prominent seaward excursion of the shoreline within the beach fill area. These modifications to the model initial bathymetric conditions were necessary to provide a more realistic representation of the starting bathymetry used in the simulations and resulted in improved agreement between model predictions and measurements, as shown by Benedet *et al.* (2006).

Additional adjustments to the model input bathymetry were made in order to develop scenarios for the effect of the different bathymetric features on beach changes and EHS development. Adjustments consisted of removing inner-shelf features such as borrow sites and/or barrier-reefs in the study area to allow for comparative analysis of model simulations conducted with/without the features of interest. The features were removed by manually deleting the depth points within polygons that covered the feature (bathymetric anomaly) of interest, and interpolating (triangular

interpolation) the remaining bathymetric data surrounding the bathymetric anomaly, similar to the approach reported in Hartog *et al.* (2008).

4.3.2. Boundary Conditions and Model Parameters

Calculations of wave statistics were based on the analysis of 20 years of hourly wave records obtained from the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory Wave Information Study (WIS) for the period between 1980 to 1999. WIS Station 463, located offshore from the south end of the nourishment project area on a water depth of 263 m (Hubertz, 1992, USACE, 2007), was used. The average deepwater significant wave height (H_{m0}) is 1 m with a period of 8.0 s, and an angle of approach from the east-northeast (64°). Excluding extreme events (hurricanes and tropical storms), higher waves with longer peak periods (i.e. 10 to 12 s) occur from October through March with predominant wave directions from northeast to east-northeast, associated with winter cold fronts. Between April and September, waves approach mostly from the east and southeast with shorter periods (3-6 s).

A wave rose plot, constructed using the 20 years of WIS data divided into 22.5° directional bands and six height classes, is shown in Figure 4.3. The line with dashes indicates the shoreline orientation. High angle NE waves dominate the wave climate in the project area by percentage of occurrence and energy (Figure 4.3). E-SE waves occur over a smaller portion of the year and occupy mostly the low energy bands (0.5 m to 1.5 m H_{m0}).

An annual wave climate consisting of schematized wave conditions was developed and imposed at the SWAN boundaries to represent one morphological year of beach change. To differentiate between sea waves and swell waves the peak period, T_p , were used. To obtain the annual wave climate a set of wave conditions was selected within seven direction sectors, each 30° wide. Two wave heights, an average condition and an extreme wave condition, were calculated for each wave direction sector. Fourteen wave cases resulted from these analyses to represent the annual wave climate of the study area. After initial evaluation of the effects of each wave condition on total sediment transport, the wave climate was reduced to six wave conditions that represent a morphologic year (Table 4.1). Reduction of the wave climate from 14 to 6 wave conditions was conducted during sensitivity analysis, where several annual simulations with/without conditions of interest were conducted and the results were evaluated comparatively. The sensitivity analysis of different combinations of the 14 conditions was conducted until the annual alongshore sediment transport magnitude predicted using the 14 wave conditions was reasonably reproduced with the reduced wave climate of 6 wave conditions. These six wave conditions include the most important wave events that occur in the study area i.e. longer period swell waves from the northeast (northeasters), and short-period wind waves from the S-SE commonly occurring during summer months. Waves induced by Hurricanes and Tropical storms are also indirectly represented since those conditions were included in the wave record used to calculate the average wave characteristics per direction sector.

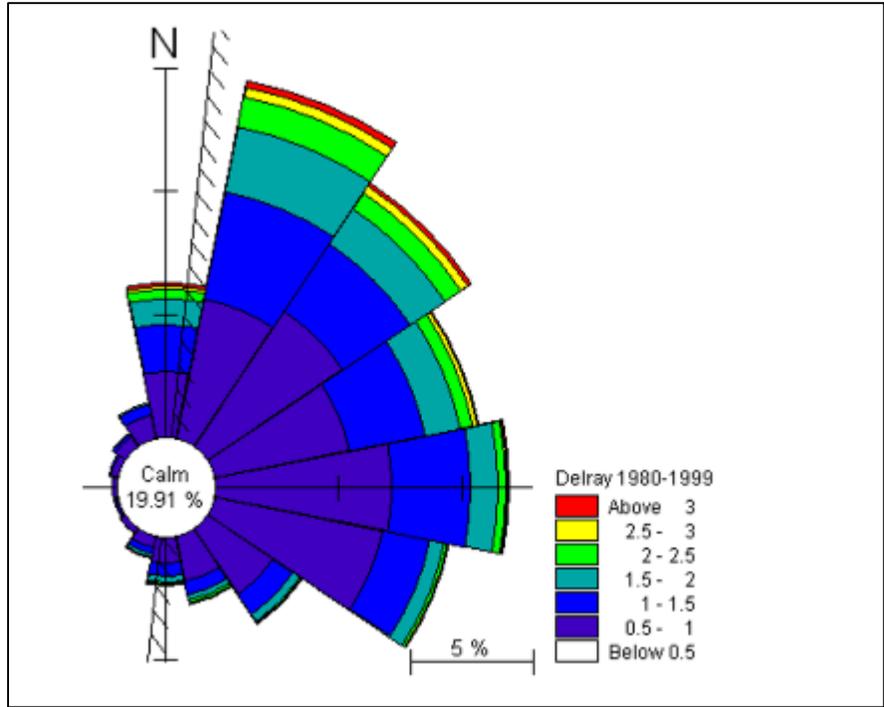


Figure 4.3. Wave rose showing frequency and direction distribution of H_{m0} for the 20 years WIS wave hindcast period (1980 to 1999). The data was classified in 22.50 direction bands and six wave height classes.

A JONSWAP spectral space shape was used in SWAN with a peak enhancement factor of 3.3. Direction spreading varied with the wave period. A wide directional spreading was used for short period wind waves while a narrower spreading were used for longer period swell waves. SWAN simulations included bottom and current induced wave refraction, diffraction, bottom friction, nonlinear triads and quadruplets wave-wave interactions, and wind-growth. Diffraction played an important role in model predictions as discussed by Benedet et al. (2006). SWAN parameters were left at their default values since no wave data for calibration of SWAN was available. Sensitivity analysis demonstrated qualitatively similar results with variations of significant wave height, wave period, directional spreading, and bottom friction values.

Table 4.1. Wave conditions used to simulate a morphological year. Fourteen wave conditions were simulated initially, based on analysis of sediment transport results per condition these wave cases were combined and reduced to the six wave conditions shown below.

Condition	Days/year	H_s (m)	T_p (s)	Dir ($^\circ$)	Wind (m/s)	Dir ($^\circ$)
a	130	0.8	5.5	45	5	45
b	12	2	11.5	60	7.75	60
c	8	2	8	135	6	135
d	8	1.8	9.5	90	7	90
e	23	2	11.5	30	8.25	30
f	87	0.7	3.5	135	4	135

Local winds are mainly influenced by two weather systems. During the winter wind blows often from the northeast due to winter cold fronts. Summer months are dominated by subtropical southeasterly and southwesterly trade winds. These general conditions are sometimes interrupted by extreme weather events such as hurricanes and tropical storms. Representative wind conditions

(velocity and direction) associated with each wave condition was derived from a 20 years' time-series available from the WIS hindcast station (Table 4.1).

Flows calculated in Delft3D-Flow were forced by the radiation stress gradients from the representative wave conditions (Table 4.1) and by tides and winds. For sediment transport the sediment online version of Delft3D-FLOW, that continuously updates sediment transport and bed level changes at every flow time-step, was used. The suspended sediment was computed over the entire water column and the bed load transport was computed for a reference height above the bottom. The sediment transport module used here is the default formulation in Delft3D, developed by van Rijn (1993). Morphological acceleration factors (morfac) were used to scale up morphology changes so only a fraction of the duration the hydrodynamic simulations was required to obtain the annual beach morphology change (Lesser et al., 2004). The morfac is a multiplication factor accounted for every flow timestep that allows for significant reduction in computation time of long-term morphology simulations. For example, a wave condition that occurs 16 days a year can be simulated in the model for 4 days, with a multiplication factor (morfac) of 4, so that 16 days are represented in terms of morphology change.

North, east and south boundaries were defined as open boundaries. The fourth boundary was the shoreline in the west. Water level data, measured over the period of 1995 to 2004, were analyzed to obtain the tidal range; MHW occurs at NGVD + 0.52 m (NGVD, National Geodetic Vertical Datum), MSL at NGVD + 0.12 m and MLW at -0.29 m. The east boundary was defined as an open boundary where the water level is given by the harmonic representation of the tide with a still water elevation of the mean tide level (NGVD +0.12 m) and an amplitude of 0.40 m, corresponding to the mean tide amplitude of the study area. Water level gradient, Neumann type boundary (Roelvink and Walstra, 2004), were used in the north and south. Two tide cycles are simulated for model spin-up time before morphological changes are computed. An average sediment grain size of the project area of 0.30 mm (Benedet et al., 2007) was used.

As in SWAN, most parameters were kept on their default values in Delft3D-Flow. Bottom roughness was expressed with the default Chezy value of 65 $m^{0.5}s^{-1}$. Sensitivity tests demonstrated that higher Chezy values corresponded to higher current magnitudes as one would expect, although qualitatively current patterns remained similar. Thus the default value was used here.

The sensitivity of model results was tested in response to different combinations of free model parameters in Delft3D. It is believed that the results presented here are qualitatively robust within reasonable ranges of model parameters, which are suitable for relative analysis the model scenarios simulated. No attention is given to absolute model predictions.

4.3.3. Beach Profile Measurements

Beach volume change measurements are conducted on an annual basis at Delray Beach as part of a continuous beach monitoring program. Beach profile measurements are conducted at monuments defined by the State of Florida Department of Environmental Protection (DEP). The profile lines are located at approximately 300 m intervals throughout the project area (Figure 4.1).

Onshore data were collected using standard differential leveling techniques encompassing an automatic level, a twenty-five 7.5 m fiberglass survey rod, and a laser range finder with prism and compass. Elevations are taken at approximately 10 m intervals along each profile line and at all breaks in slope.

The nearshore portion of the survey (submerged profile) extended seaward of the monuments to a depth of approximately -10 m NGVD (National Geodetic Vertical Datum). Depth measurements were collected at approximately 7 m intervals with final processed data reflecting a maximum interval of 15 m. Depth soundings were conducted by a boat-towed sea-sled equipped with RTK differential GPS.

4.4. RESULTS & DISCUSSION

4.4.1. Measured Beach Volume Changes

Annualized beach volume changes per unit length of beach ($\text{m}^3/\text{m}/\text{yr}$) after the three most recent beach nourishment projects (1984, 1992 and 2002) were calculated (Figure 4.4). The volume changes were calculated between toe of the dune of each beach profile to the -10 m water depth. The 1984 project was constructed between monuments 176 and 188 extending about 4.2 km alongshore while the 1992 and the 2002 beach nourishment projects were constructed between monuments R180 and R188, extending about 3 km alongshore (Figure 4.1). Nearly 940,000 m^3 of sand ($313 \text{ m}^3/\text{m}$) were placed in both the December 1992 and the March 2002 nourishment projects and 1,000,000 m^3 was placed in 1984. Unit volume placed on the beach varied, higher volumes were placed in areas that showed greater erosion since the last renourishment and vice-versa.

Offshore bathymetric features that may influence project performance include dredged borrow areas, and shore parallel reefs (Figure 4.1). Quasi-circular deep borrows areas (i.e. 10 to 12 m depth of dredge cut) in Figure 4.1 were dredged in the early 1970s and in 1978 while the rectangular shallower cuts (2 to 3 m depth of dredge cut) were dredged in the 1990s and in 2002. While the 1984 to 1992 and 1992 to 2000 time periods were a relative calm period in terms of Hurricanes and Tropical storms in the project area, the time period between March 2003 and May 2005 was marked by a record number of severe storms, included Hurricanes Frances and Jeanne in 2004, and Hurricane Wilma in 2005. The effect of these events on beach volume changes is readily visible in Figure 4, the 2003 to 2005 time period showed greater volume losses and greater alongshore variability in beach changes relative to the other two longer time-periods shown (1984-1992 and 1992-2000).

During the three time-periods shown in Figure 4.4 erosion was observed within the fill area and beaches to the north and south of the fill were either stable or accretion. An average volume loss of $7 \text{ m}^3/\text{m}/\text{yr}$ was observed between 1984 to 1992, compared to a loss of $21 \text{ m}^3/\text{m}/\text{yr}$ between 1992 and 2000, and a loss of $41 \text{ m}^3/\text{m}/\text{yr}$ between 2003 and 2004.

Overall differences between beach response in the different time-periods shown in Figure 4.4 are attributed to variations in the wave climate, possibly the effects of additional borrow sites dredged for each project and length of the record (higher losses are commonly observed in the first few years after nourishment construction, i.e. Benedet et al., 2007). The higher erosion rates

measured during the last time period, for example, are likely due to the combination of impacts of several Hurricanes and Tropical storms that affected the project area during this timeframe and shorter duration of the record.

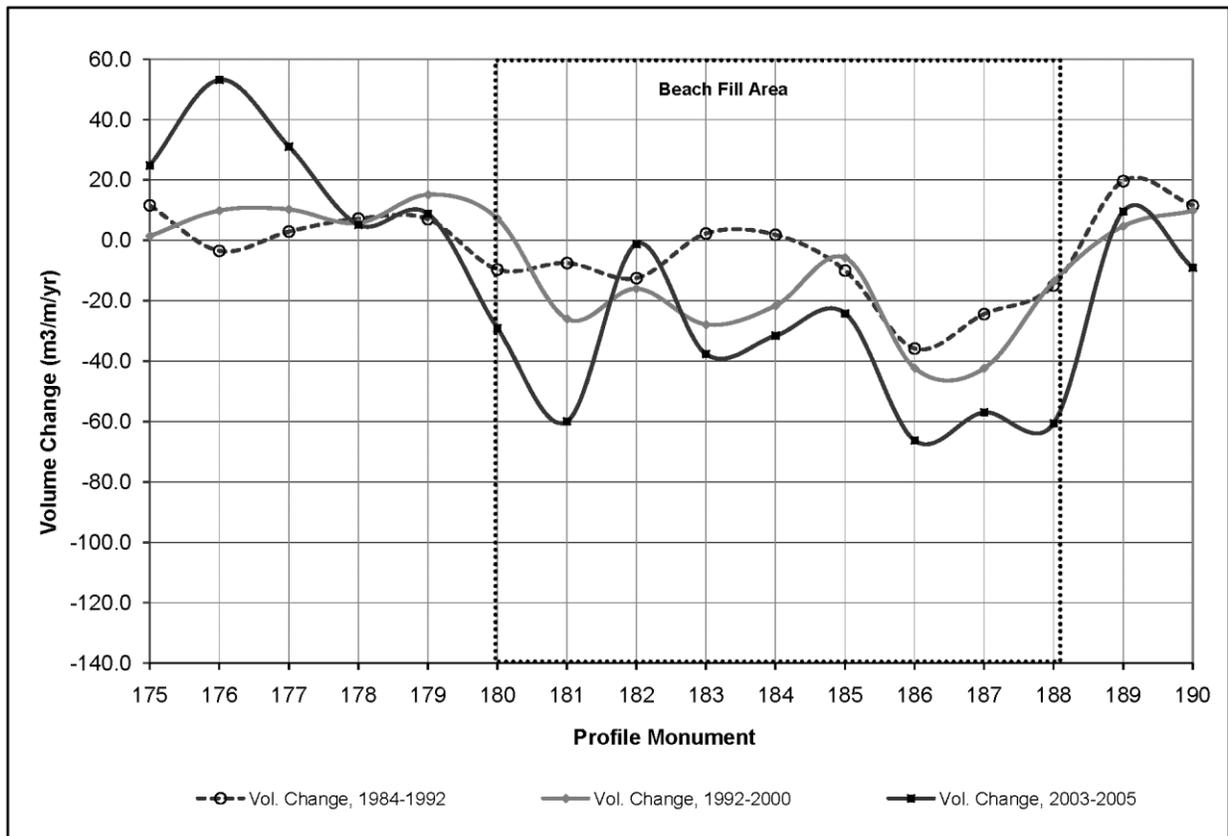


Figure 4.4. Volume change observations for three different time-periods: 1. 1984 post construction to 1992 pre-construction, 2. 1992-post construction to 2000 pre-construction, and 3. 2003 post-construction to 2005.

Nonetheless, one common feature of all time periods shown in Figure 4.4 is the higher erosion observed between beach profile monuments R186 to R187, when compared to other project segments. The average erosion at this segment is four times higher than the project average from 1984 to 1992, two times higher than the fill average from 1992 to 2000 period and 1.6 times higher from the 2003 to 2005. Because of the overwhelming signature of higher erosion at this relatively short (600 m long) beach segment, the following sections of this paper will focus on the evaluation of the causes of the higher erosion at this beach segment. Based on previous work done by Benedet et al. (2007) and Hartog et al. (in press) we assume that the model is simulating the magnitude of erosion in this area reasonably well (see Figure 4.2) and therefore it can be used to compare model performance under different bathymetric scenarios, allowing the evaluation of physical processes underlying model predictions.

4.4.2. Comparison of Simulated Beach Volume Change under Different Bathymetric Scenarios

To evaluate the effects of borrow areas on fill evolution, annual beach morphology change runs using three different bathymetric scenarios were conducted, the scenarios were: (1) existing

conditions, (2) bathymetry without older deep borrow areas, (3) bathymetry without all borrow areas. A contour plot illustrating the different bathymetries used is shown in Figure 4.5.

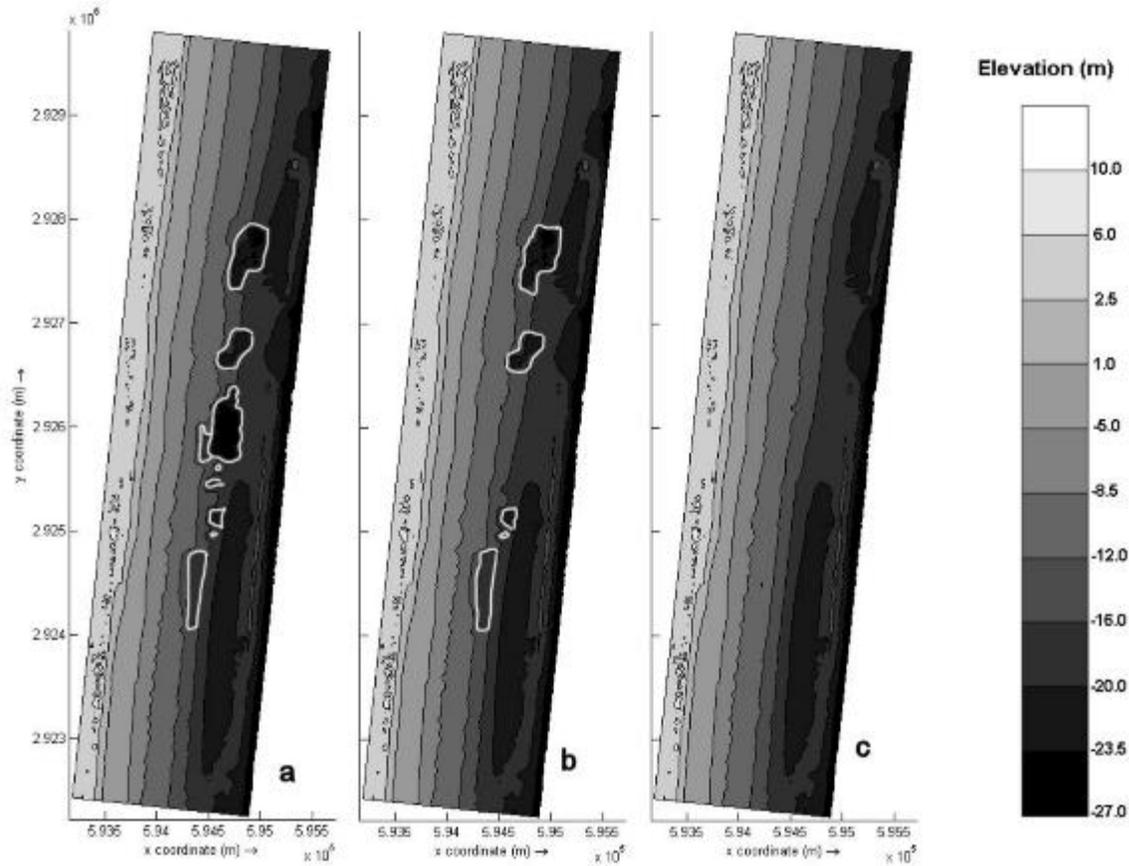


Figure 4.5. Bathymetric scenarios used in the model simulations. Bathymetry representing the existing condition is showing on the first plot to the left, the center plot shows the bathymetry without a deep dredge pit located in the center of the project area, the plot to the right shows the bathymetry without all dredge pits.

Relative volume changes that show the difference between the simulations with different bathymetric scenarios and the existing conditions were calculated by subtracting the volume change predictions for the modified scenarios from the volume change prediction of the existing condition. The resulting plot (Figure 4.6) shows the effect of the bathymetric features (dredge pits) on beach volume changes. A positive value represents a positive effect from removal of the dredge pit, indicating that the bathymetric features were causing beach erosion. Conversely a negative value indicates a negative effect from removal of the dredge pit from the model domain, which indicates that the bathymetric features were causing beach accretion in the affected area.

Effects of removing the deep borrow site were not significant between R180 and R181 (north end of the fill and north of borrow limits) (Figure 4.6). The effects were negative (more sand loss in relation to existing conditions due to borrow removal) at profile monuments R184, R185, R188

and R189. The effects were significantly positive (less sand loss or deposition in relation to existing conditions) in the erosion hot spot area (between R186 and R187) (Figure 4.6).

Effects removing all borrow sites were negative at profile monuments adjacent to the fill ends (R179 and R189) and between profiles R184 and R185 (Figure 4.6). Effects were positive in the north segment of the fill, especially at profile monuments R181 and R183, and at the erosion hot (between R186 and R187, see Figure 4.6).

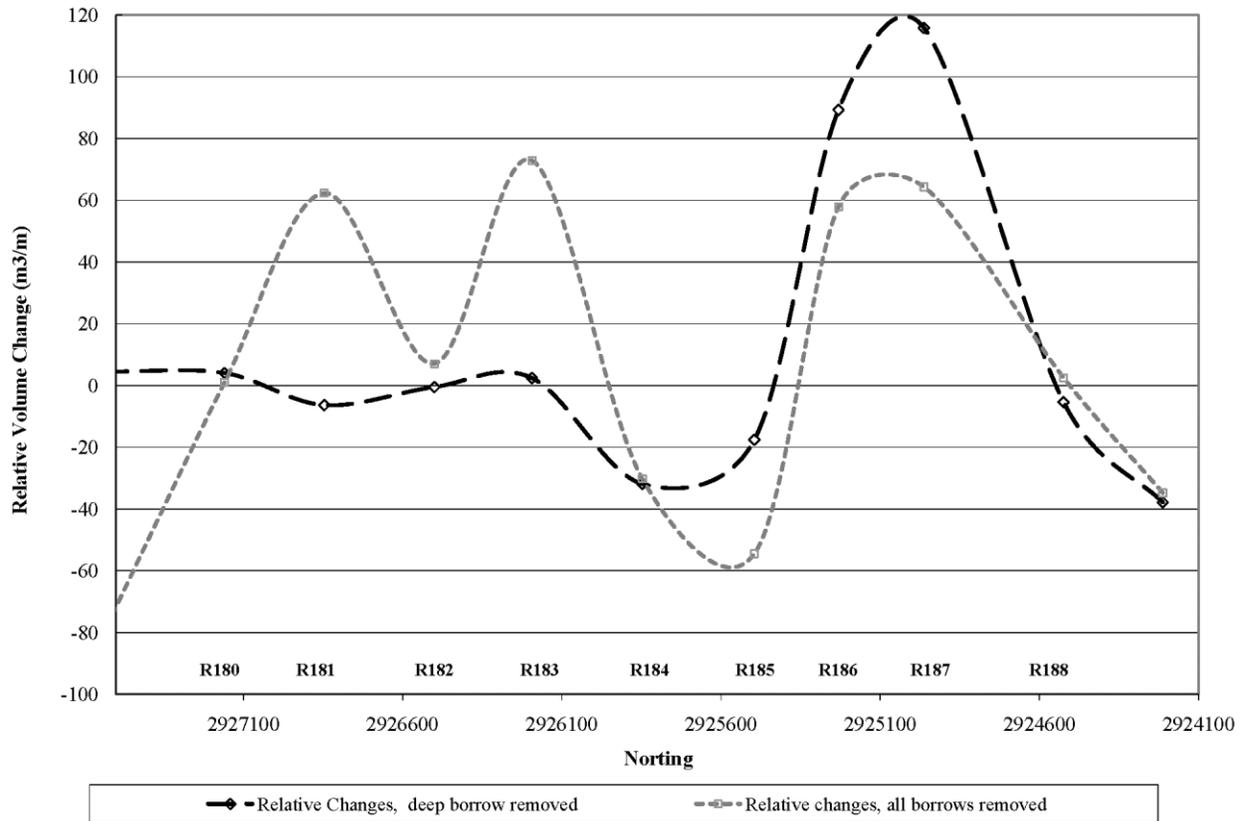


Figure 4.6. Relative beach volume changes showing the volume changes associated with the bathymetric scenarios simulated compared to the existing conditions simulation. Relative volume changes were calculated by subtracting annual beach volume change predictions for the scenario simulations by the simulation of existing conditions.

Both scenarios (deep borrow area removed and all borrow areas removed) caused benefits (accretion) at the previously eroding hot spot segment (R186-R187). Conversely the same scenarios caused negative impacts (extra erosion) at the previously stable beach segment located updrift from the hot spot (R184-R185), and downdrift of the hot spot (R188-R189). The benefits resultant from the removal of the borrow areas range from +75 m³/m to +120 m³/m at the erosional hot spot segment, which corresponds to the amount of erosion previously observed and predicted by the model in this area (see Figure 4.2). This observation indicates that the dredge pit, especially the ‘deep borrow area’ dredged in the 1970s is the main cause of the erosion hot observed in the southern end of the fill (R186 and R187). After borrow area removal, model simulations indicate

that extra erosion in this area is drastically reduced. Processes causing the erosional hot spot downdrift of the borrow area are evaluated in the following sections of this paper.

The variability of beach volume changes is smaller for simulations without the borrow areas than for the existing conditions (Table 4.2). This phenomenon occurs because the borrow areas cause gradients in wave height throughout the project (i.e. Benedet *et al.*, 2007, Hartog *et al.*, 2008), these gradients in turn induce flow cellular circulations, especially during shore normal waves, and gradients in sediment transport which in turn cause different segments of the beach to respond (erode) with different magnitudes causing the high standard deviations in Table 4.2.

It is interesting to note in table 4.2 that, even though the erosion hot spot area is responsible for about 50% of the volume losses from the project site (Benedet *et al.*, 2007), reducing volume losses from this area (i.e. by removing the borrow areas) does not translate into reduction in loss from the project area proportionally. This occurs because the borrow sites cause areas of accentuated erosion but also accretion along the beach fill. Processes behind these erosion and accretion areas are evaluated in the following section.

4.4.3. Schematic Model of Borrow Area Effects and Erosion Hot Spot Formation

In both modified bathymetric scenarios (deep borrow removed and all borrows removed) the erosion at the EHS segment is reduced by 70 m³/m/yr to 120 m³/m/yr (Figure 4.6). Because the total erosion in the erosional hot spot area ranged from 80 m³/m to 100 m³/m in the existing condition simulations, these results suggest that removing the borrow areas by backfilling, especially the deep borrow site dredged in the 1970s, would significantly reduce or eliminate the severe erosion currently observed in the hot spot segment.

Comparison of simulations with and without the deep borrow site indicated that the same deep borrow area has minor influence in the north end of the project (north of dredge pit), has a positive effect between R184 and R185 (directly onshore and slightly south of dredge pit) and a noticeable negative effect, at R186-187 (between 600 and 1000 m south of the dredge pit).

To evaluate the effects of wave transformation patterns in alongshore currents, sediment transport and morphology change a schematic area model was developed. The simplified schematic area model approach was adopted to allow for elimination of noise signal from other sources (offshore reefs, shallower borrow sites, shoreline orientation and nearshore bar morphology), emphasizing, in this way, the signature from one single, deep cut dredge pit (12 m depth of cut) on the adjacent beach. This schematic model extended 8 km alongshore and 4 km cross-shore. The model uses shore-parallel contours that were created using the equilibrium profile equation (Dean, 1991) for a beach grain size of 0.3 mm. A borrow area similar to the Delray Beach deep borrow area was included in the model domain. This borrow has a rectangular shape, a depth of cut of 12 m, extends 750 m alongshore and 380 m cross-shore and is located between the seabed elevation contours of 11 m to 14 m.

The numerical model parameters used in the schematic model are similar to the Delray Beach model. Model boundary conditions consisted of a wave case with Hs of 2 m, 10 s peak period and an angle of 45° with the shore. No winds or tides were included in the simplified schematic model. The model was run for 45 days with bathymetry update to provide a clear, although exaggerated,

picture of the borrow area effects on nearshore hydrodynamics and erosion and sedimentation patterns.

Results are summarized in Figure 4.7. Hydrodynamic results were extracted in the end of the model spin-up time period, which was 12 hrs. The borrow area is located between $Y=2500$ m and $Y=3350$ m. Because waves approach the area with a 450° angle, a distinguishable wave shadow zone (area with lower wave energy) occurs to the right of the borrow area, between $Y=3300$ m and $Y=4200$ m. Wave focusing (increase in wave energy) occurs to the right (between $Y=4200$ m and $Y=5000$ m) and left of this wave shadow zone (between $Y=2300$ m and $Y=3200$ m) (Figure 7a).

Lower water levels occur in the wave shadow zone, especially between $Y=3500$ m and $Y=4000$ m, and higher water levels occur to the left (between $Y=2500$ and $Y=3000$ m) and right ($Y=4000$ m to $Y=4500$ m) of this zone (Figure 4.7b). The distribution in water levels by itself cause head gradients that would in turn force a flow from the zones of high water level (wave focusing zones) to the area with lower water level (wave shadow zone). This would indicate a head-gradient based flow from the left to right between $Y=2500$ m and $Y=3500$ m, and a flow from right to left between $Y=3500$ m and $Y=4500$ m. Waves on the other hand, are approaching the coast at a 450° angle, from left to right, thus the net wave induced flow is from left to right, and the net flow direction and transport will be mainly a result from the balance of the forces induced by the head gradient and incoming waves angles. This force balance is investigated more closely in the next section.

Flow velocities predicted by the model are shown in Figure 4.7c. Current velocities are stronger between $Y=2000$ m and $Y=3500$ m and between $Y=5000$ m and $Y=6000$. Slower currents occur between $Y=4000$ m and $Y=4500$ m. A gradual current deceleration occurs between $Y=3500$ and $Y=4000$, and a gradual current acceleration occurs between $Y=4500$ and $Y=5000$. Slower currents occur in the transition between the wave shadow zone and the wave focusing zone to the right. Surprisingly high current velocities occur throughout most of the wave shadow zone. It is speculated that this occurs because both the hydraulic head gradient and the wave forces induce a transport from left to right, both force components are in-phase, thus current velocities are amplified. Of particular interest are the transitional zones, decelerating currents between $Y=3500$ and $Y=4000$ would induce a decreasing sediment transport capacity, while accelerating currents between $Y=4500$ and $Y=5000$ would cause an increasing transport capacity.

Potential sediment transport (combined suspended and bedload, in $m^3/m/s$), resulting from wave and current forcing, is shown in Figure 4.7d. Potential sediment transport is higher between $Y=2000$ and $Y=3500$, and between $Y=5000$ and $Y=6000$ and reaches minimum values between $Y=4000$ and $Y=4500$. As previously speculated the transport capacity decreases between $Y=3500$ and $Y=4000$ and gradually increases between $Y=4500$ and $Y=5000$ (Figure 4.7d). The latter observation is particularly important to beach erosion and deposition patterns behind the borrow site. A decreasing transport capacity (downward sloping sediment transport curve) would cause beach accretion (more sediment coming in to an area than leaving it), which would persist through the zone of low transport. As transport capacity gradually increases (upward sloping sediment transport curve) additional erosion occurs (less sediment coming in to an area than leaving the area). This erosion would persist until the sediment transport is stabilized (flat sediment transport curve).

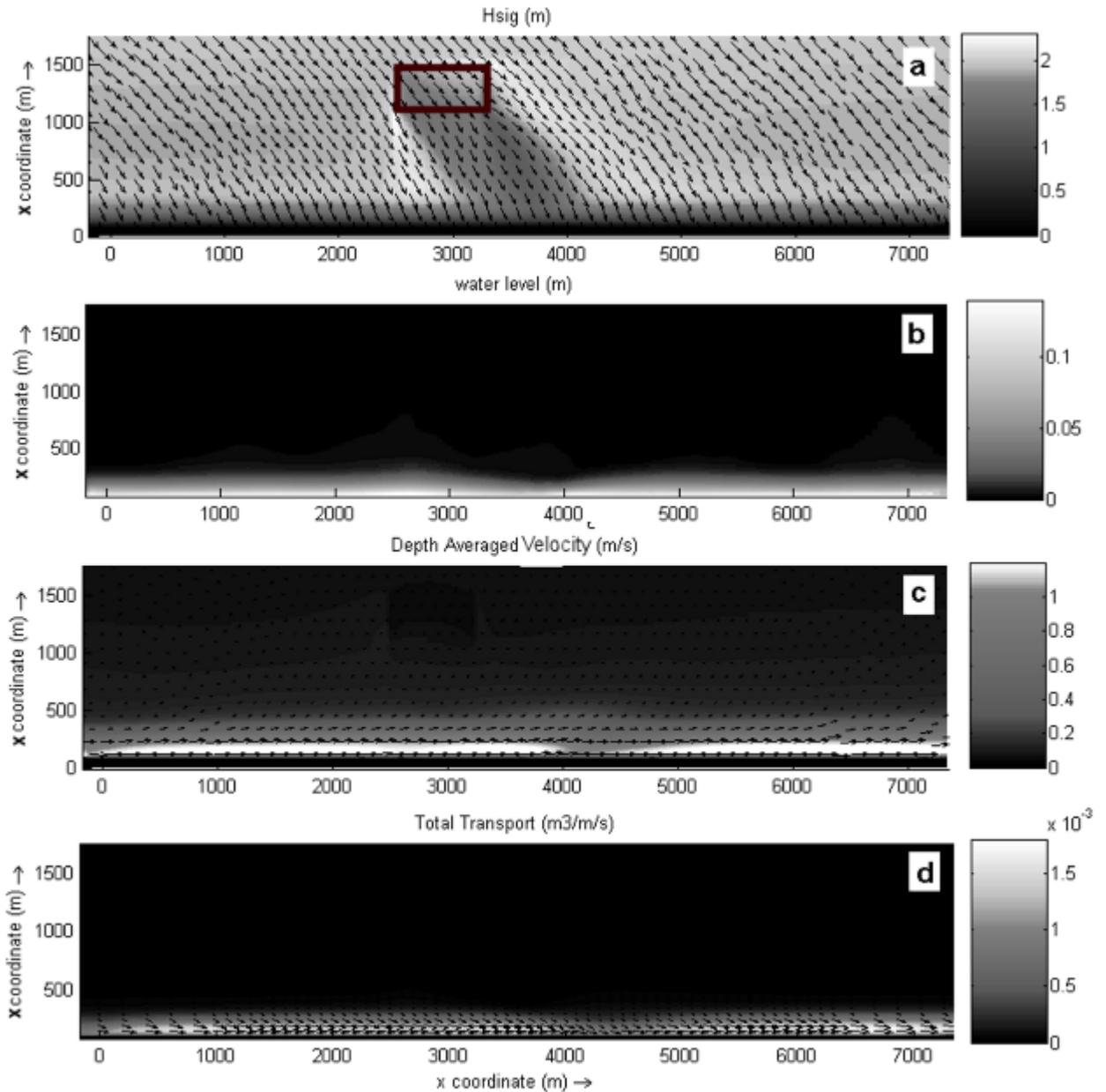


Figure 4.7. Wave height, water levels, flow and sediment transport predicted in the schematic model. The figure allows the identification between showing zones of wave shadow (divergence of wave rays) and concentration of wave energy (convergence), gradients wave induced setup (water levels), and gradients in flow velocity and sediment transport magnitude.

Predicted erosion and deposition patterns, after 45 days of simulation, are shown in Figure 8. A distinguishable accretion zone, which lead to the formation of a beach salient, occurs between $Y=3500$ m and $Y=4500$ m, indicating beach accretion caused by the dredge pit. To the left of this accretion zone ($Y=2000$ m to $Y=3500$ m) there are alternating zones of erosion and deposition across the profile, with quasi-neutral volumetric change. Of particular interest is the zone between $Y=4500$ m and $Y=5500$ m (Figure 4.8). High erosion, disproportional to the other segments of the

model, is observed in this zone throughout the entire beach profile, indicating beach erosion caused by the dredge pit. This high erosion zone, occurs immediately downdrift of the accretion salient, indicates the possible formation of a borrow-area induced erosion hot spot, which is a product of the increasing transport capacity in this area.

It is interesting to note that, because of the 45° angle of approach of the incoming waves the accretion zone occurs between 500 m and 1500 m to the right of the borrow area centroid, not directly behind it. The erosional hot spot created by such a feature occurs between 1500 m and 2500 to the right (downdrift) of the dredge pit. The location of the erosion and deposition zones would obviously shift around depending on the local wave climate. Sensitivity analysis conducted here shows that as the waves become more shore normal the deposition zone gradually shifts towards the area directly behind the borrow site, and the downdrift erosion zone shifts with it.

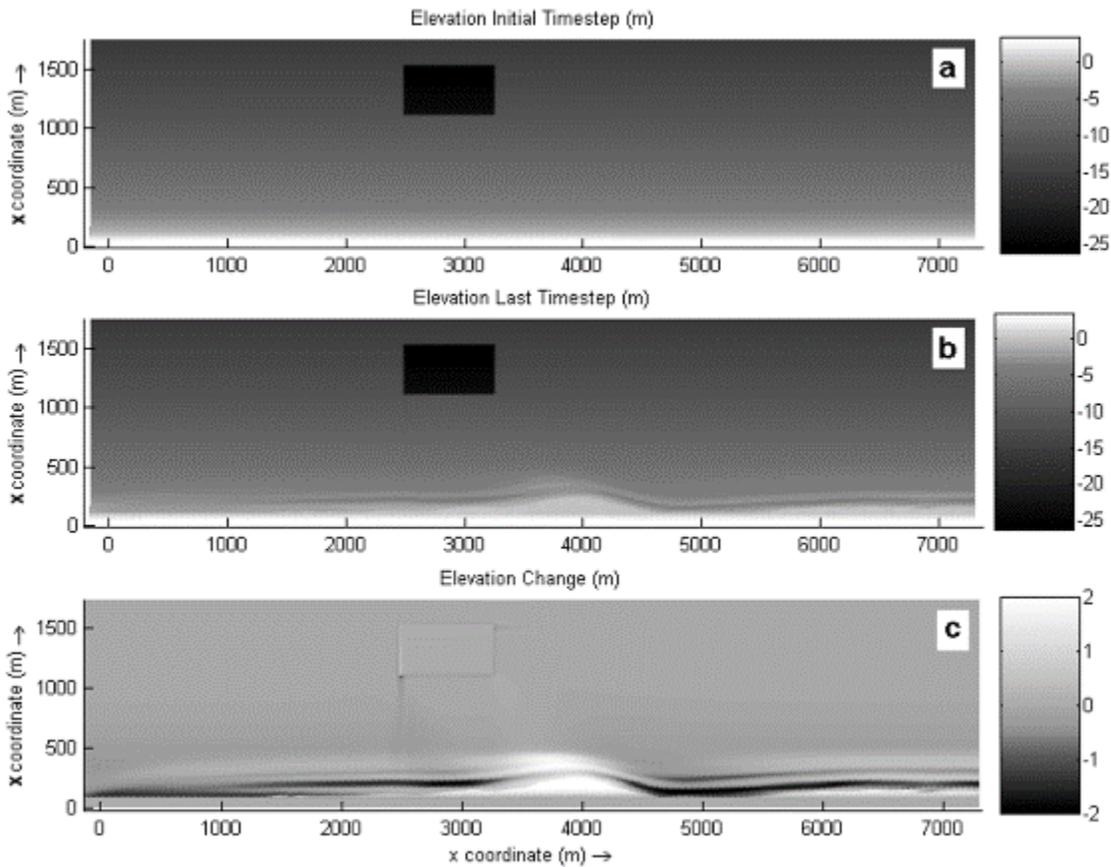


Figure 4.8. Initial bathymetry, final bathymetry (after 45 days), and erosion/deposition predicted by the model. Accretion zone occurs between $x=3500$ and $x=4500$, and severe erosion, disproportional to the other segments of the model, is observed between $x=4500$ and $x=5500$.

4.4.4. Forces Controlling Flows behind the Borrow Site

To evaluate the importance of different forcing on the flow and sediment transport patterns observed behind the dredge pit in the schematic case, the components of the time-averaged, depth-

integrated, steady-state, alongshore momentum balance in terms of Delft3D forces were evaluated as:

$$\rho(h+\eta)v\frac{\partial v}{\partial y} = \frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} + \rho g(h+\eta)\frac{\partial \eta}{\partial y} + \tau_{by}, \quad (1)$$

where the term on the left side of Equation 1 is the advective acceleration of the alongshore velocity, which correlate to alongshore currents, and on the right side of Eqn. 1 the first two terms are the radiation stress gradients responsible for longshore flow, the third term is the pressure gradient force (resulting from alongshore variations in wave setup), and the fourth term is the bed shear stress. The two radiation stress terms are combined and obtained as the alongshore component of the “roller force” from Delft3D output. If the forcing terms on the right side of Eqn. 1 add up to the advective acceleration on the left side of Eqn. 1, the momentum equation is considered balanced and terms which have been neglected here ($u\partial v/\partial x$ and lateral turbulent mixing) are assumed to be negligible.

The result of the Delft3D momentum balance analysis is given in Figure 4.9 (4.9a to 4.9d) for an alongshore transect at a location close to the outer segment of the surfzone. The sum of the forces shown individually in panels b,c,d is compared to the advective acceleration term in panel a, demonstrates that the forcing terms isolated in Eqn. 1 explain most of the variations in alongshore flow. Both the radiation stress gradient and the pressure gradient play a major role in contributing to the pattern in the advective acceleration, while the bed shear stress acts as a stabilizer and limiter of flow accelerations. For comparison of the forces with flow, sediment transport and erosion/deposition patterns the figure uses the same x-scale as figures 4.7 and 4.8. The decomposition of forces shown in Figure 4.9 can be broken down into three main segments in order to explain the flow variability behind the dredge pit (and indirectly the erosion and deposition patterns):

- **Segment 1 (between Y=2500 m and Y=3500 m):** The flow velocity is increasing to the right in this zone (Figure 4.9a, positive values). Although the roller force is diminishing slightly but still forcing flows to the right (Figure 4.9b), the pressure gradient term is increasingly positive (Figure 4.9c) causing the flow velocity from left to right to increase. The bed shear stress increases as the flow velocity increases (Figure 4.9d), limiting the flow increase. Zone 1 is directly behind the borrow site and under the high-angle waves simulated it is a slightly erosional zone.
- **Segment 2 (between x = 3500 m and x = 4500 m):** The flow velocity is decreasing to the right within this zone (mostly negative values in Figure 4.9a). At first this results from a rapidly decreasing roller force (Figure 4.9b) as the pressure gradient term remains nearly constant (Figure 4.9c). The flow continues to slow down as the roller force starts to increase again (Figure 4.9b) because the pressure gradient term decreases and reverses its sign forcing the flow from the right to the left, opposite to the direction of the roller force term. In other words, the flow forced by the gradients in wave-setup (pressure gradient term) is pointing to the opposite direction as the flow forced by the wave angle of incidence (roller

force). These two forces partially cancel each other and the result is a slower alongshore current. Towards the end of this zone, the flow stops decreasing because the roller force continues to increase (Figure 4.9b) while the pressure gradient term becomes less negative (Figure 4.9c). Zone 2 is accretion.

- **Segment 3 (between $x = 4500$ m and $x = 5500$ m):** The flow is accelerating to the right in this zone (positive values in Figure 4.9a). At the beginning of this zone the roller force is increasing (Figure 4.9b) and the pressure gradient term (Figure 4.9c) is becoming less negative, explaining flow acceleration. However, for much of the zone roller force is constant and pressure gradient term is zero, yet the flow continues to accelerate. This is because flow velocities start out at a minimum in this zone, and thus the bed shear stress is low (Figure 4.9d). As the flow increases the bed stress increases until it limits the flow at around $x = 5500$ m, where the shear stress stabilizes and becomes constant. Zone 3 is highly erosional and could be characterized as an erosional hot spot (see Figure 4.9).

The changes behind the borrow site are thus due to the interaction of wave forces (roller force), differentials in wave setup (pressure gradient term), and variable bed shear stress. Accretion associated with such features is due to decreasing wave heights in the shadow zone that causes decreasing roller force, and due to out-of-phase flows induced by the wave forces and the pressure gradient forces. Current acceleration and erosion hot spot development downdrift of the accretion zone is mostly due to flow accelerations as the gradients in wave setup (pressure gradient term) becomes insignificant, the shear stress is still low, the wave forces gradually increase to normal levels. Under these circumstances the flow velocities gradually increase until it reaches an equilibrium with local shear stress.

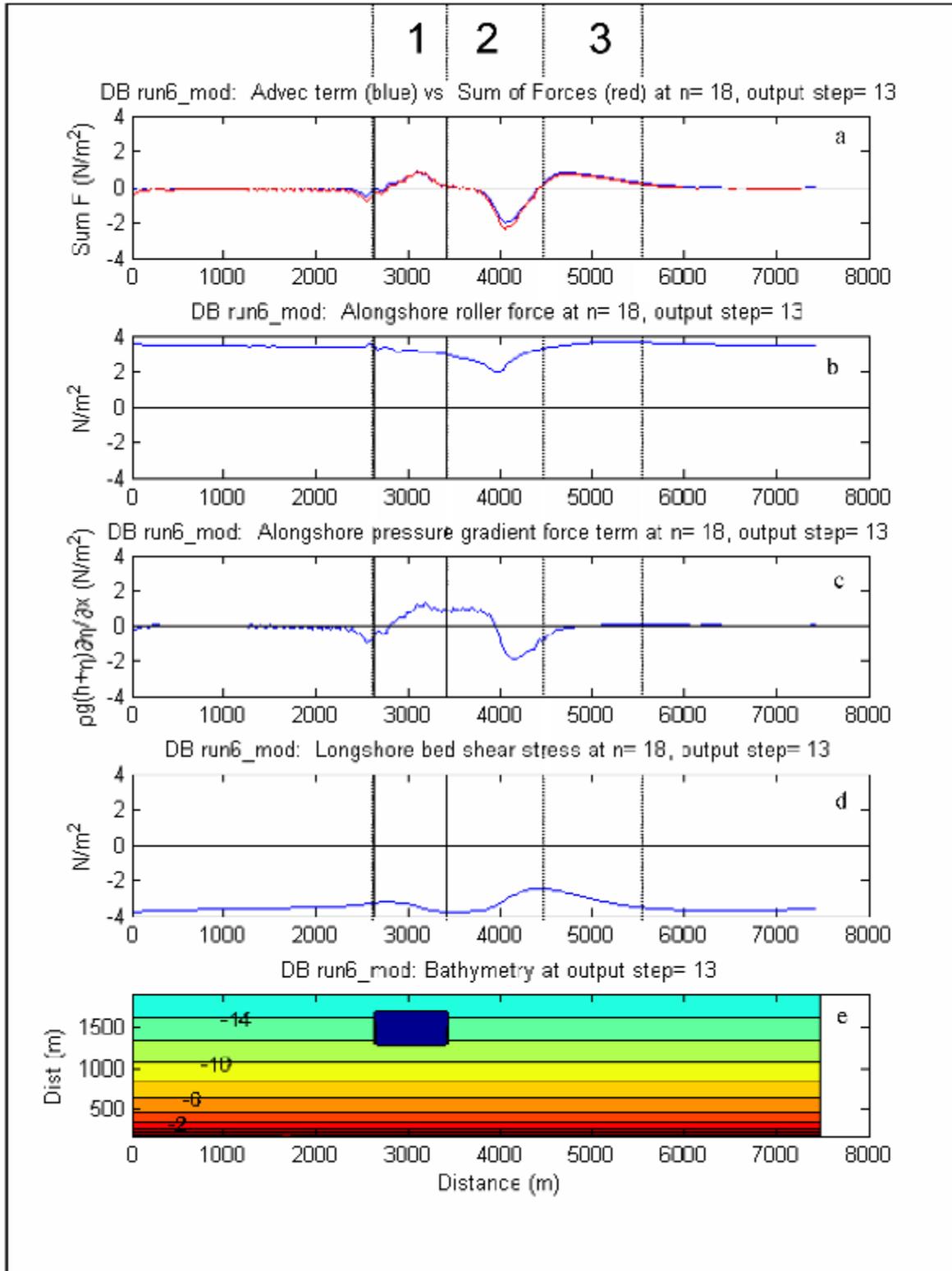


Figure 4.9. Momentum balance forces. The sum of the forces shown individually in panels b (roller force),c (alongshore pressure gradient force), and d (longshore bed shear stress) is compared to the advective acceleration term in panel a, demonstrating that the forcing terms isolated explain most of the variations in alongshore flow.

4.4.5. Relevance to the Delray Beach Case Study

Net alongshore sediment transport in the case-study (Delray Beach) is from north to south, swell waves from the NE, with an angle of incidence ranging from 300° to 750° , dominate beach changes in the study area (see boundary conditions section). High angle swell waves (i.e. 30 to 60 degrees shore normal, 8 s to 12 s) from the NE are common in the study area during winter months. The propagation of these high waves, is strongly influenced by the dredge pits in the project area (Benedet et al., 2006, 2007, Hartog et al., 2007). Under this wave climate, the beach segment at the north end of the borrow area and directly behind it, to about 800 m downdrift (between R184 and R185) is more stable than the rest of the nourishment area (Figure 4). Downdrift of the stable area an erosional hot spot occurs, between 8000 m and 2000 m to the south of the borrow site (R186 to R187, Figure 4). Temporal shifts in the location of the stable area and the erosional hot spot can occur with annual changes in the wave climate, however, over the long-term, the beach monitoring data have shown that these two zones show persistent trends of beach stability (R184 to 185) and extra beach erosion (R186 to R187), the latter defined as an erosional hot spot.

Processes similar to those described in the schematic model are believed to be causing the erosional hot spot at Delray Beach. Previous hypotheses used to explain the erosion hot spot at this location included variations in beach grain size (Fernandez, 1999) and changes in shoreline orientation (Benedet et al., 2006). The additional analysis and model simulations shown in this study however strongly suggest that the offshore dredge pits, particularly the deeper-cut pit dredged in the 1970s, is the main cause of the erosion hot spot.

The dredge pits cause both the erosion hot spot at R186 and R187, but also promotes beach stability between R184 and R185, thus removing the borrow area by backfilling will reduce volumetric losses from the erosional hot spot segment but also may have adverse effects on the beach segments between R184 and R185.

4.4.6. Implications to the Design of Borrow Areas and Offshore Coastal Structures

Human interventions on the coast that affect wave propagation patterns along the shoreline (wave shadow and focusing zones), be it a dredged pit, a breakwater or a submerged reef, will likely cause downdrift erosion in adjacent areas. Downdrift erosion occurs in most situations where gradients in wave height are induced, due to similar processes described in the schematic model. That is, flow and sediment transport potential will gradually decrease towards the wave shadow, causing a depositional zone, and gradually increase again towards the non-sheltered zone, causing additional erosion until the shear stress increases and flow velocity is stabilized, and consequently the alongshore sediment transport system is re-established.

Wave manipulation to create a beach depositional zone may be non-intentional, as is the case for most dredge pits, but it can also be created intentionally for shore-protection purposes, as is the case for artificial submerged reefs. One must be aware, however, that an increase in sediment transport potential from the wave shadow area (the protected area) to the neighboring areas would cause localized erosion. Once a trend of increasing sediment transport potential is established, sediment transport continuity says that erosion will occur since more sand is leaving a given beach segment than coming in to the segment. Even though submerged structures are ‘permeable’, i.e.

they allow flow and transport behind the structure, to be effective (cause deposition) they have to modify the sediment transport system, and by definition will cause some downdrift erosion.

With the recent advances in morphological modeling one can reasonably estimate the magnitude and geographical locations of beach erosion and deposition zones that may result from nearshore dredging projects, or placement of offshore structures. With such estimates a sensitivity analysis of possible adjustments to the design of these features can be made, in order to develop optimized designs that minimize such downdrift impacts to tolerable levels.

Empirical relationships commonly used to estimate shoreline response to offshore structures such as breakwaters and submerged reefs (i.e. Dally and Pope, 1986, Sunamura and Mizuzo, 1987, Sanderson and Elliot, 1996, Black and Andrews, 2001), provide an incomplete answer, since they address only the estimates of benefits (i.e. salient growth), disregarding adjacent erosion zones. These erosion zones, as demonstrated here, develop as a result of the modifications in the nearshore wave patterns and resultant spatial gradients in flows and longshore transport, that is, the same processes that cause the development of the accretion salient intended by design.

4.5. CONCLUSIONS

A numerical modeling study utilizing Delft3D was conducted to evaluate the effects of bathymetric features such as dredged borrow areas on the formation of hot spot erosion hot spots (EHS). The study utilized two model domains that resembled the conditions at Delray Beach.

A borrow area with a 12 m maximum depth of cut, located in the center of the Delray Beach project area about 1 km offshore, was identified as the main cause for the EHS in the south end of the project, which is located between 1 km and 1.5 km downdrift of the borrow site. The hot spot is responsible for about 50% of the erosion from the project site, removing the borrow area by backfilling reduces the hot spot erosion drastically but also increase erosion in areas there is beach accretion or stability.

Physical processes causing the observed behavior were investigated using a simplified schematic model. Using the schematic model it was demonstrated that the beach changes behind the borrow site are due to the interaction of wave forces (roller force), differentials in wave setup (pressure gradient term), and variable bed shear stress. These processes cause a unique pattern of flow and sediment transport distribution behind bathymetric anomalies. Decrease in current velocity and sediment transport occurs towards the wave shadow zone, causing deposition of sediments and beach accretion. The lowest currents are observed in the downdrift end of the shadow zone and into the beginning of the wave focusing zone, because pressure gradient forces currents in an opposite direction as the wave induced flow. Current acceleration and erosion hot spot development downdrift of the accretion zone is due to flow accelerations as the gradients in wave setup (pressure gradient term) becomes insignificant, shear stress is still low, and the wave forces gradually increase to normal levels. Under these circumstances the flow velocities gradually increase until it reaches equilibrium with local shear stress. This leads to a gradual increase in sediment transport capacity (upward sloping sediment transport curve) and conditions favorable to EHS development. This process persists until current velocity and sediment transport is stabilized by the increased bed shear stress.

Both the case study and the schematic model showed that in areas where high angle waves are common, erosion and deposition zones caused by a dredged pit can occur at a relatively far downdrift of it (up to 2 km downdrift in this study). The location of the erosion and deposition zones may shift around depending on inter-annual variations in the wave climate. Sensitivity analysis show that as the waves become more shore normal the deposition zone gradually shifts to the area directly behind the borrow site, and the downdrift erosion zone shifts with it.

The results imply that human interventions that affect nearshore wave propagation patterns along the surf-zone, causing wave shadow and focusing zones will cause downdrift erosion in adjacent areas. Offshore coastal structures designed for coastal protection, such as submerged reefs and breakwaters, will cause downdrift erosion due to the same processes operating behind dredge pits. The downdrift erosion zones develop as a result of the modifications in the nearshore waves and resultant gradients in flows and longshore transport, the same processes that cause the development of the accretion salient intended by design in the first place. Empirical relationships commonly used to estimate shoreline response to offshore structures such as breakwaters and submerged reefs; in this regard provide an incomplete answer, since they address only the estimates of benefits (i.e. salient growth), disregarding the magnitude of adjacent erosion zones.

Recent advances of morphological modeling allows coastal scientists and engineers to reasonably estimate the magnitude and geographical locations of beach erosion and deposition zones, which may result from nearshore dredging projects, or placement of offshore structures. With such estimates a sensitivity analysis of possible adjustments to the design of these features (borrow areas and coastal structures) can be made, in order to develop optimized designs that reduce downdrift impacts to a manageable level.

CHAPTER 5. EFFECTS OF NEARSHORE DREDGE PIT DESIGN PARAMETERS ON THE EROSION AND ACCRETION PATTERNS OF ADJACENT BEACHES

Abstract

The magnitude of the effects of nearshore dredge pits on adjacent beaches depends on a range of parameters, including seabed geomorphology, local wave climate, sediment supply, and pit design characteristics (e.g. distance offshore, depth of cut, cross-shore and alongshore extents, shape of pit). Delft3D, a morphological model developed by Deltares, was used to investigate relationships between dredge pit design parameters and impacts on adjacent beaches. The purpose of this study was to identify design parameters that affected the magnitude of dredge pit effects on adjacent beaches. An ancillary purpose was to develop a scientific basis for dredge pit design recommendations for beach restoration and other sediment needs of coastal infrastructure projects. Dredge pit design sensitivity tests were conducted using Delft3D. A schematic model was constructed using shore-parallel contours and tests for a single-wave condition and for an annual wave climate. The depth of the cut and the cross-shore length of the dredge pits greatly influenced the magnitude of the dredge pit impacts on the adjacent beaches. The distance of the borrow pits from the shore influenced the magnitude and location of the impacts (because of the oblique wave incidence). An inverse relationship was verified between the water depth in which the dredge pit was located and the magnitude of its impacts on adjacent beaches. Dredge pit impacts on adjacent beaches can be reduced significantly by designing narrow, elongated parabolic pits with a shallow cut depth. Depth of cut increments had pronounced effects in shallow water (2–6 m), but in water depths greater than 8 m, gradual depths of cut increments of 2 m did not significantly affect its impact on adjacent beaches. Results of this study indicate that the effects of dredge pits on adjacent beaches can be reduced significantly by adopting optimal pit designs while maintaining the same dredging volume.

This chapter is based on the following publications:

Benedet, L., Finkl, C.W., and Dobrochinski, J.P.H. 20012. *Optimization of Nearshore Dredge Pit Design to Reduce Impacts on Adjacent Coasts*. *Journal of Coastal Research*, 29 (3), 519–525.

Benedet, L., and List, J.H., 2008. Evaluating the Effects of Dredge Pit Design Parameters on Erosion and Accretion of Adjacent Beaches. in: *Proceedings of the 31st International Coastal Engineering Conference* (Hamburg, Germany, ASC), pp. 629–647.

5. 1 INTRODUCTION

Beach nourishment is employed preferentially as a mitigation procedure along eroded shores around the world (Finkl and Walker, 2002). Consequently, large volumes of sand are used to restore eroding beaches. In the United States, for example, project sediment volumes between 13106 m³ and 23 106 m³ are common, with some nourishments approaching volumes on the order of 10 3 106 m³ (e.g. Miami Beach and Panama City Beach) (Finkl, Benedet, and Campbell, 2006). Large volumes of sand are also used in other engineering applications, such as the construction of ports and breakwaters. Because large sediment volumes cannot be efficiently and economically trucked to the beach, sand deposits on the inner shelf are a common sediment source. The dredging of sedimentary blanket deposits, such as interreefal sand flats and sand ridges, however, introduces large anomalies in nearshore bathymetry that, in turn, influences wave transformation, nearshore currents, and sediment transport patterns. Gradients of sediment transport induced by nearshore dredge pits effect patterns of beach change, causing zonation in beach erosion patterns, development of erosional hot spots, and sediment deposition that results in zones of beach accretion (e.g. Bender and Dean, 2003; Benedet, Finkl and Hartog, 2007).

Relative impacts of nearshore dredge pits on adjacent beaches depend on parameters, such as seabed geomorphology, local wave climate, and pit design (e.g. distance offshore, depth of cut, and cross-shore and alongshore extent). We summarize results of a numerical modeling sensitivity analysis that investigated the impacts of dredge pit design parameters on potential beach response. The purpose of this analysis was to identify design parameters that influence the magnitude of dredge pit effects on the adjacent beach. Related to this purpose was the desire to provide a scientific basis for design recommendations that could reduce unwanted onshore impacts. Sensitivity tests used a process-based morphodynamic model (Delft3D) developed by Deltares (Lesser et al., 2004). Results were evaluated in terms of beach volume change, which was compared against a baseline simulation (i.e. no dredge pit).

5.2. METHODS

The schematic Delft3D numerical model developed for this study consisted of two nested wave-model grids and one flow-morphology grid nested inside the refined wave-model grid. The schematic model used hypothetical bathymetry that consisted of parabolic (shore-parallel) contours. The morphological model-grid dimensions were 10 km alongshore and 2.5 km cross-shore. Grid cell spacing ranged from 100 m at distal model boundaries to 15 m in the area of interest (dredge pits and shore). All model free parameters were kept constant and were based on the author's previous work (Benedet and List, 2008a,b; Benedet, Finkl, and Hartog, 2007; Hartog et al., 2008). The free parameter settings included (1) a wave-bottom friction defined as $C_{\text{jon}} 0.067 \text{ m}^2 \text{ s}^3$, (2) a flow Chezy friction factor of 65, (3) a flow horizontal eddy diffusivity of 1, and (4) a horizontal eddy viscosity of 1. The Roller model of Reniers, Roelvink, and Thornton (2004) was activated in the wave-driven hydrodynamic computations. The sediment transport module used the default formulation in Delft3D, developed by van Rijn (1993). Transport parameters included a multiplication factor for suspended sediment reference concentration (SUS) and bed-load transport vector magnitude (BED) of 0.75, a wave-related suspended sediment transport factor (SUSW), and a wave-related bed-load sediment transport factor (BEDW) of 0.1, a dry-cell erosion

factor (Thetsd) of 0.5, a sediment grain size of 0.3 mm, and a constant bottom sediment thickness of 10 m along the entire domain of simulation, inclusively below the depth of cut inside the dredged pits. A morphological acceleration factor was used to scale up morphological changes such that only a fraction of the duration of the hydrodynamic simulations was required (Lesser, 2009; Ranasinghe et al., 2011). The computations were conducted in three-dimensional (3D) mode, with five vertical computational layers of hydrodynamics, each layer occupying 20% of the water column.

Model tests were performed for a single-wave condition, with a significant wave height of 2 m, 8-second peak period, 15° angle of approach (from the shore-normal), 20° directional spreading, JONSWAP (Joint North Sea Wave Project) spectrum, with a peak enhancement factor of 3.3, and a morphology simulation period of 30 days. Tests were also conducted for an annual wave climate created for the SE coast of Florida, used previously by Benedet, Finkl, and Hartog (2007), Hartog (2006), and Benedet and List (2008b). However, the wave angles were rotated 95° to the left because the model was defined with face due north (2708–908 alongshore axis), which differs from the orientation of the SE coast of Florida (58– 1858 alongshore axis). The annual wave climate is described in Table 5.1. The wave cases used a JONSWAP directional spectra; that is, directional spreading values in the annual wave climate were defined as a function of wave peak period (narrower spectra for longer period and vice versa).

The dredge-pit design parameters tested were depth of cut, design shape with different cross-shore and alongshore lengths, water depth in which the dredge pit was located, and dredge-pit distance from the shore.

Table 5.1. Annual wave climate used in the 1 year simulations. A Total of 303 days were simulated, 61 days correspond to days where the ocean was flat (less than 0.5 m deepwater Hsig) or when the mean wave direction was directed to the offshore.

Hsig (m)	Tp (s)	Direction (degrees)	Number of Days
0.8	5.5	315	145
2	11.5	330	15
2	7	45	10
1.8	9.5	360	10
2	11.5	315	26
0.7	3.5	45	98

Depth-of-cut model-sensitivity simulations consisted of simulating a rectangular dredge pit in 10m of water, 1.5 km from the coast, with lengths of 400m cross-shore and 800m alongshore, at several dredge-cut depths (between 1 m and 15 m).

Design-shape model-sensitivity simulations consisted of simulations of a dredge pit with a total volume of 1.33 10⁶ m³, 1.5 km from the coast in about 10 m of water depth. Different dredge pit shapes were designed by modifying cross-shore and alongshore length relationships. Dredge pit dimensions (cross-shore by alongshore length) were 100m by 3200m, 400 m by 800 m, 600 m by 553 m, and 800 m by 400 m.

Model-sensitivity simulations of the dredge-pit water depth were based on a borrow area located 1.5 km from the coast with the following dimensions: 400 m cross-shore by 800 m alongshore and a 4 m depth of cut, for a total volume of $1.33 \times 10^6 \text{ m}^3$. The water depth where the dredge pit was located was modified by varying the slope of the seafloor. This strategy was adopted in lieu of moving the dredge pit further offshore to isolate water depth effects from others such as distance from shore. Nearshore and onshore impacts were simulated for dredge pits located at water depths of 8 m, 10 m, 12 m, 15 m, and 22 m.

For the dredge-pit distance from the shore model, sensitivity simulations required a larger morphological model grid with the following numerical grid dimensions: 9 km wide cross-shore and 20 km alongshore. The simulated dredge pit, located in 12 m of water, was 400 m wide by 800 m long, with a 4 m depth of cut that yielded 1.33106 m^3 . The model bathymetry contained a flat slope, seaward of the 12 m isobath, so that dredge-pit distance from the shore could be modified with no change in the water depth. Dredge pits were located 1700, 4000, 6000, and 8000 m from the shore.

For illustrative purposes, a plan view of the morphological grid and hypothetical bathymetry used in the schematic model, a dredge pit with 800m alongshore and 400m cross-shore and an 8 m cut, is shown in Figure 5.1.

Results from the sensitivity simulations were evaluated for relative beach volume changes. The relative beach volume change is defined as the difference between the baseline model simulation (no dredge pit) and the simulation with the dredge pit. Volume changes were computed to the 7 m depth contour to focus the analysis on beach changes, so that the volume change calculations were not contaminated by dredge-pit infilling or re-contouring of surrounding seafloor.

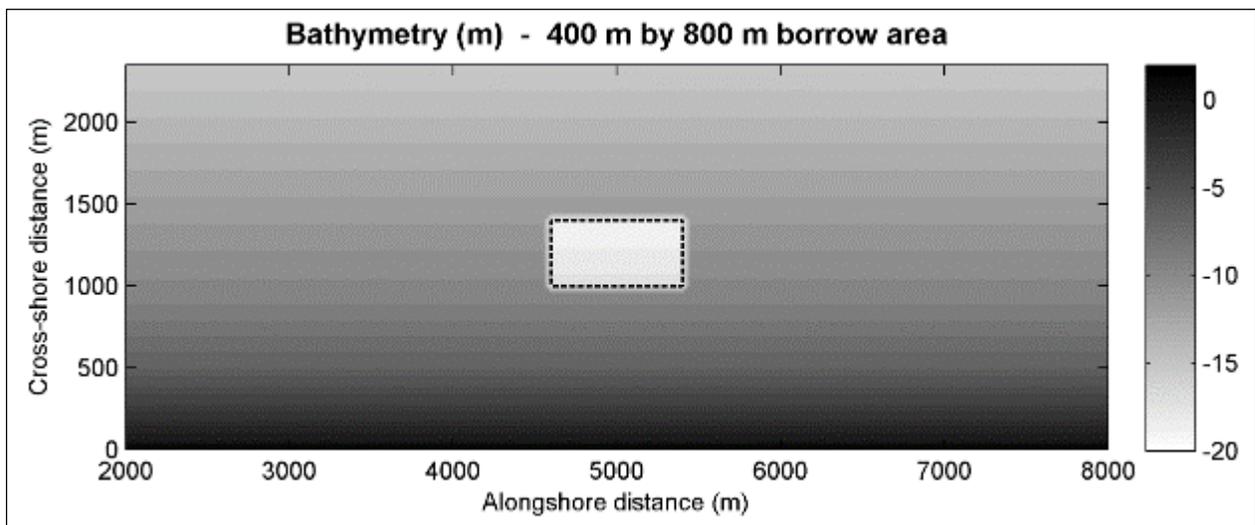


Figure 5.1. Morphological model grid for dredge pit dimensions of 800 m alongshore, 400 m cross-shore, and 8 m depth of cut. The shoreward boundary of the dredge pit is located in 10 m water depth.

5.3 RESULTS

5.3.1 Dredge Pit Depth of Cut

Relative beach volume change was simulated for different depths of cut, as shown in Figures 5.2 and 5.3. Figure 5.2 shows the results of simulations for the case of a single wave, with 30 days of morphological change and depths of the cut ranging from 1m to 15 m. The results for tests with the annual wave climate (see Table 5.1 for wave conditions) are shown in Figure 5.3.

Impacts on adjacent beaches, for the single wave condition (Figure 5.2) ranged from $-80 \text{ m}^3/\text{m}$ erosion to $+80 \text{ m}^3/\text{m}$ deposition for the 15 m depth of cut, and $-20 \text{ m}^3/\text{m}$ to $+15 \text{ m}^3/\text{m}$ for the 1 m depth of cut. Because, in this schematic, the peak wave direction is 158° from the left, the impact on the adjacent coast is more prominent on the right-hand side of the accretion zone (the downdrift segment). Despite the generally expected causal relationship between depth of cut and beach impact (*i.e.* the deeper the cut, the greater the influence of the dredge pit on the adjacent beach), there was a critical threshold where increasing the depth of cut resulted in only a minor increase in the beach erosion, in our tests this threshold was around 6m cut.

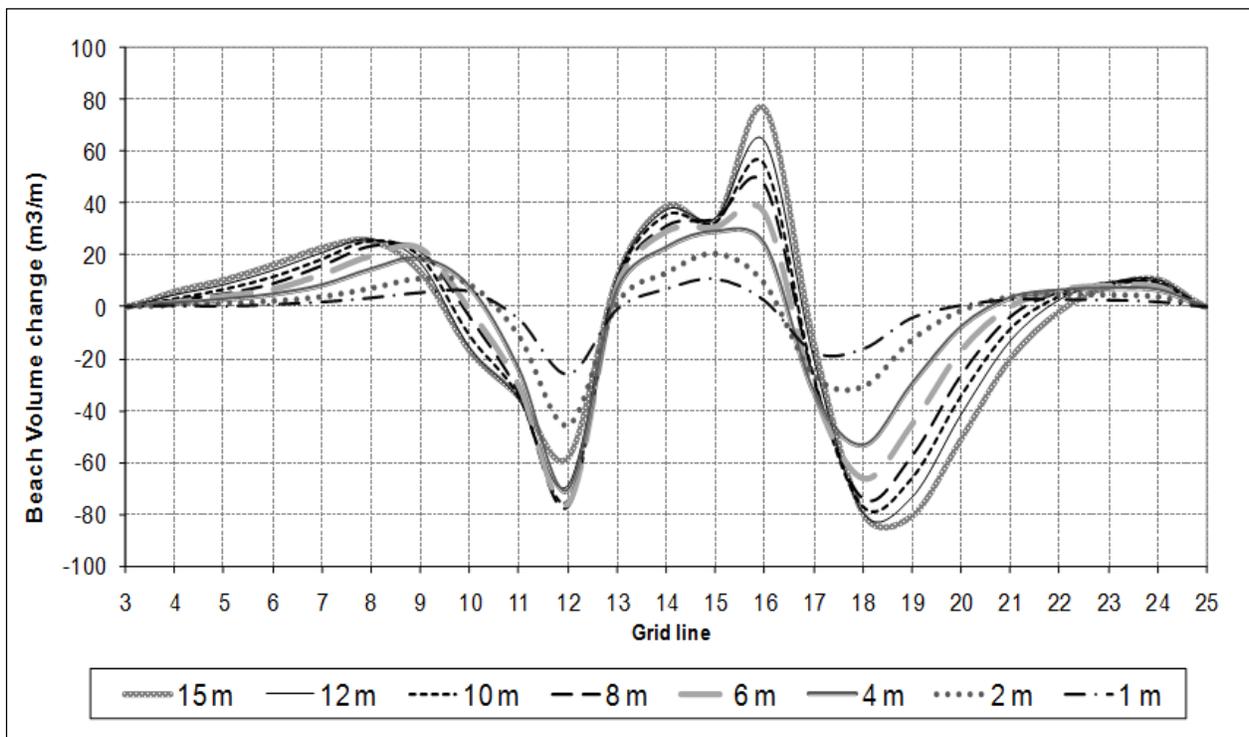


Figure 5.2. Relative beach volume changes, as a function of cut depths. Simulations used a single wave case of 2 m, 8 s peak period, and 15° angle of approach. Morphological changes were simulated for a period of 30 days with constant wave forcing. The dredge pit was located in 10 m of water depth (shoreward edge), had dimensions of 800 m alongshore and 400 m cross-shore.

Cut depths from 2 m to 10 m were tested using the annual wave climate. Impacts on adjacent beaches, for a simulation period using a schematic annual wave climate, are shown Figure 5.3. Impacts ranged from $-150\text{m}^3/\text{m}$ erosion to $+250\text{m}^3/\text{m}$ deposition for a 10-m depth of cut and ranged from $-60\text{m}^3/\text{m}$ to $+80\text{m}^3/\text{m}$ for the 2-m depth of cut. Because the dominant wave energy in this schematic was from high-angle wave bands from the left (see Table 5.1), the impact on the adjacent coast was much more prominent on the right-hand side of the accretion zone (the downdrift segment). For reference purposes, the dredge pit lies between grid lines 75 and 105 in Figure 5.3. Pattern simulations for the annual wave climate were similar to the single-wave climate, but magnitudes of erosion/deposition were greater in the annual simulation because of the longer simulation period. The short-period, lower-energy waves from the right do not cause large changes in beach volume. The beach response signature was dominated by longer-period, higher-energy NW waves. Because the mean wave-energy flux was from left to right, areas of erosion and deposition were shifted downdrift. The downdrift erosion zone occurred 1.5 to 2 km downdrift of the dredge pit.

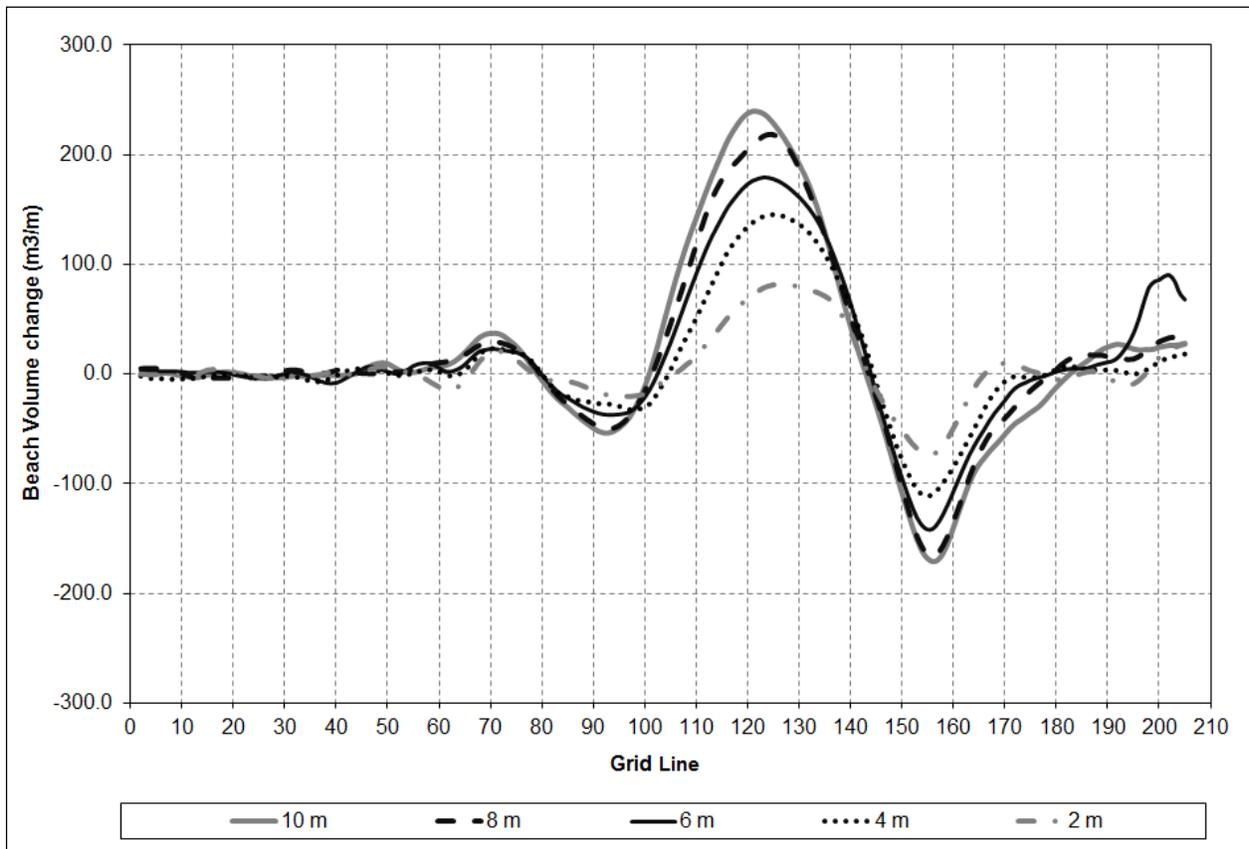


Figure 5.3. Relative beach volume changes, as a function of cut depths for one year morphological simulations. Simulations are based on an annual wave climate as shown in Table 5.1. Dredge pit parameters are the same as those in Figure 5.1.

Similar to the single-wave case simulations, increments in the depth of cut in the lower range (2 m to 6 m depth of cut) produced the largest rate of change on the magnitude of erosion/accretion. The increment of cut depths from 8m to 10m was associated with a reduced rate of change in the

magnitude and location of beach volume changes caused by dredge pit dredging. Around grid line 200, in Figure 5.3, there is a distinct morphologic change pattern. That area, however, was close to the model boundaries and was not directly influenced by the dredge pits; therefore, it is not discussed further in this article. Because patterns between single and annual wave cases were similar, but of different magnitude, this article focuses on simulations that show larger beach volume changes in relation to the annual wave climate.

5.3.2 Dredge Pit Shape

In the dredge-pit shape simulations, the depth of cut was kept constant at 4 m, but the ratios between cross-shore and alongshore lengths were varied, keeping the pit volume constant at $1.3 \times 10^6 \text{ m}^3$. Dredge pit dimensions (cross-shore by alongshore length) were 100m by 3200m, 200m by 1600m, 400 m by 800 m, 600m by 553m, and 800m by 400m. Examples of two different dredge pit configurations are shown in Figure 5.4.

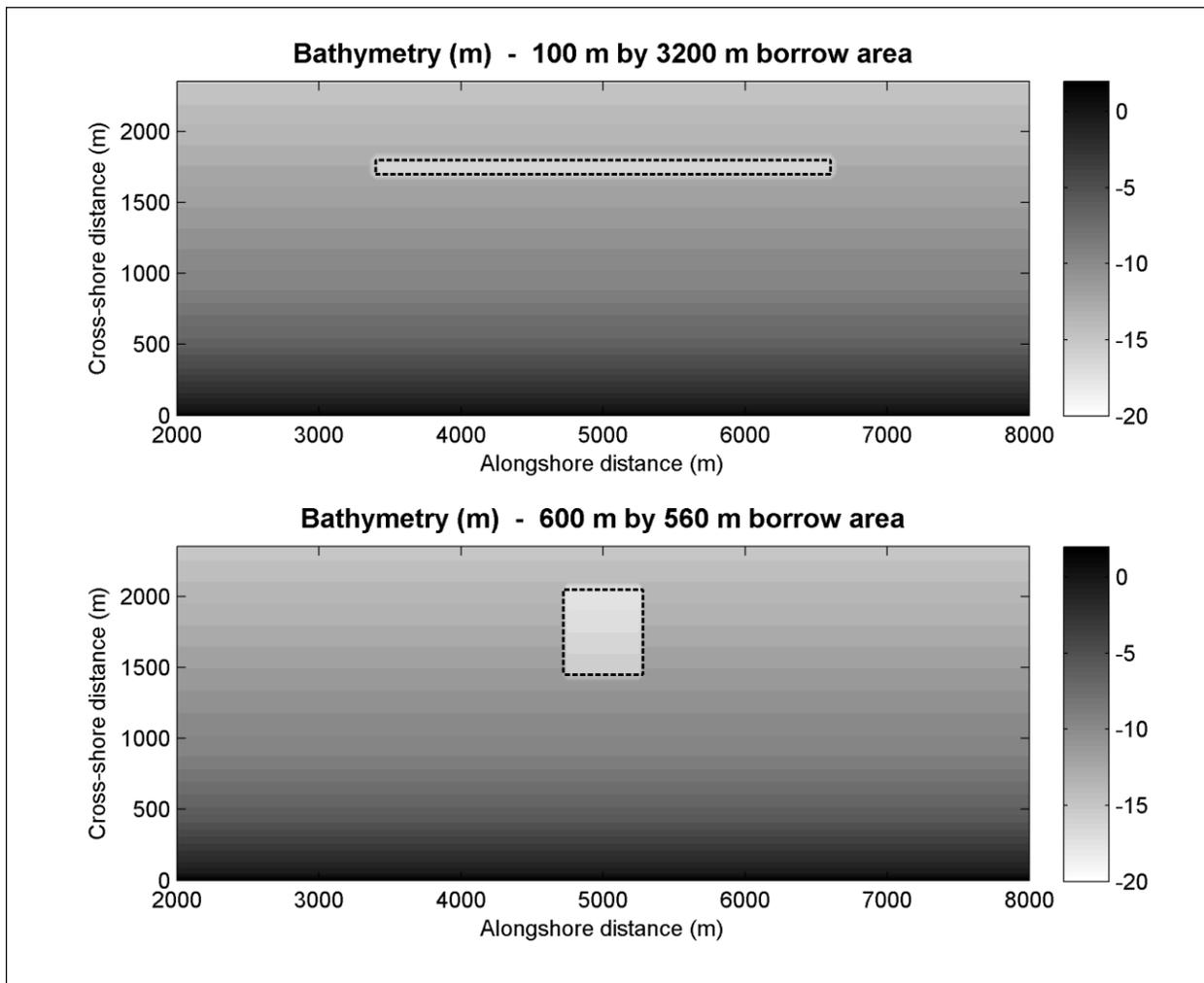


Figure 5.4. Schematic model bathymetry for two different borrow area design scenarios: (1) 100 m cross-shore by 3200 alongshore and (2) 600 m cross-shore by 560 alongshore to produce long, narrow and equant exemplars.

Relative beach-volume changes for the different dredge pit cross-shore lengths tested, using the annual wave climate, are shown in Figure 5.5. For a dredge pit with a cross-shore length of 800 m, beach volume changes ranged from $-150\text{m}^3/\text{m}$ erosion to $+190\text{m}^3/\text{m}$ deposition. For a dredge pit with a cross-shore length of 100 m, beach volume changes ranged from $-55\text{m}^3/\text{m}$ erosion to $+50\text{m}^3/\text{m}$ deposition. The long, narrow dredge pit (100 m cross-shore by 3200 m alongshore) had three to four times less effect on beach volume change while maintaining dredge pit volume. Similar impacts on beach volume change were observed for cross-shore widths of 100 m and 200 m as well as for 600 m and 800 m. The critical dimension affecting the magnitude of beach volume change occurred between 200 m to 400 m cross-shore widths (Figure 5.5).

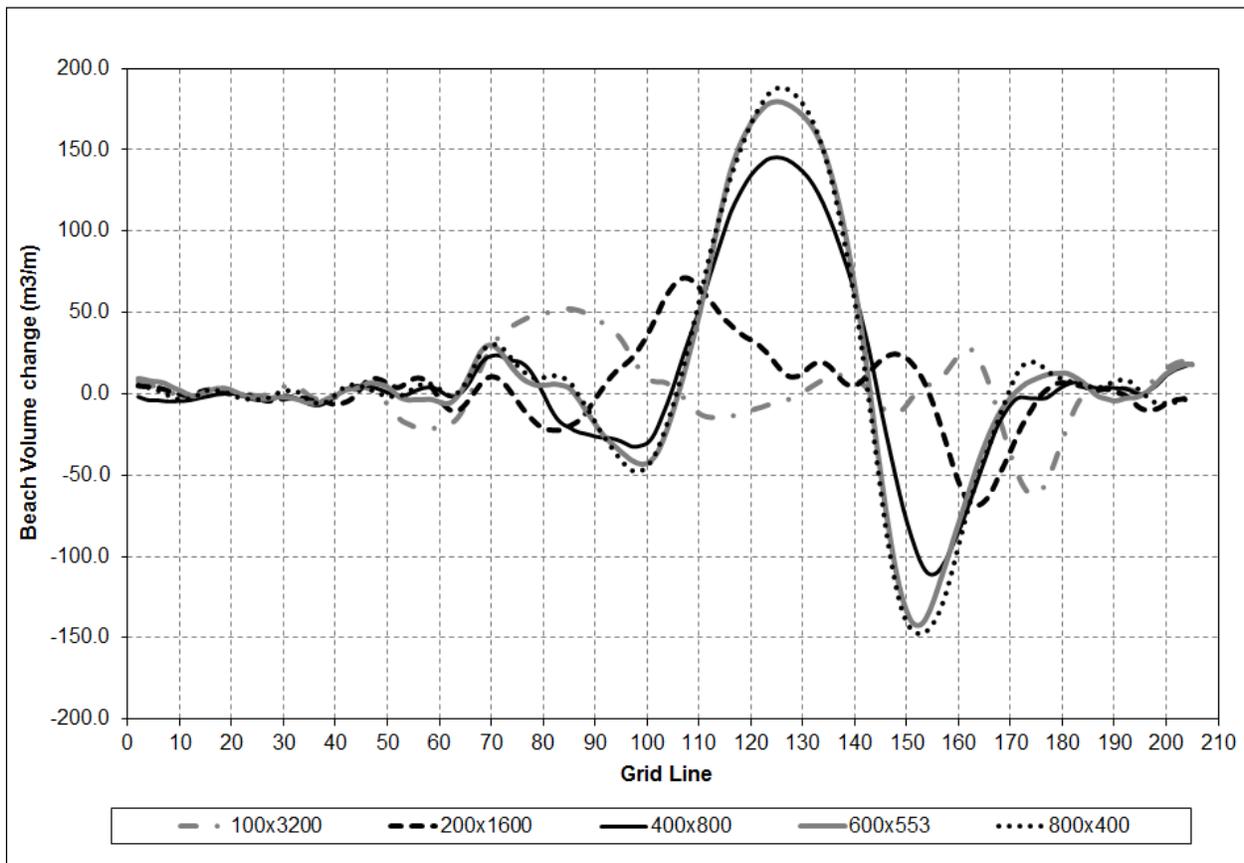


Figure 5.5 Relative beach volume changes, as a function of dredge pit shape. Results from the simulations of one year of morphological change using the annual wave climate shown in Table 5.1. The dredge pits simulated were located in 10 m water depth (shoreward edge), a 4 m depth of cut and a volume of approximately $1.3 \times 10^6\text{m}^3$.

5.3.3 Dredge Pit Situated in Different Water Depths

The effect of the water depth of the dredge pit siting on the magnitude of the beach volume change was evaluated by isolating it from the other parameters. Simulations were based on a borrow located 1.5 km from the shore, with dimensions of 400m cross-shore by 800m alongshore, a 4 m depth of cut, and a constant volume of $1.3 \times 10^6\text{m}^3$. To modify water depth without affecting other parameters, the slope of the seafloor beyond the depth of the closure was manipulated. This strategy was adopted in lieu of moving the dredge pit further offshore to isolate the effects of water

depth. Dredge pits were simulated at water depths of 8 m to 9 m (1:1000 slope), 10 m to 11.5 m (1:500 slope), 12 m to 14 m (1:250 slope), 15 m to 19 m (1:125 slope), and 20 m to 30 m (1:62 slope). Cross-shore profiles showing the different bathymetric scenarios simulated are shown in Figure 5.6.

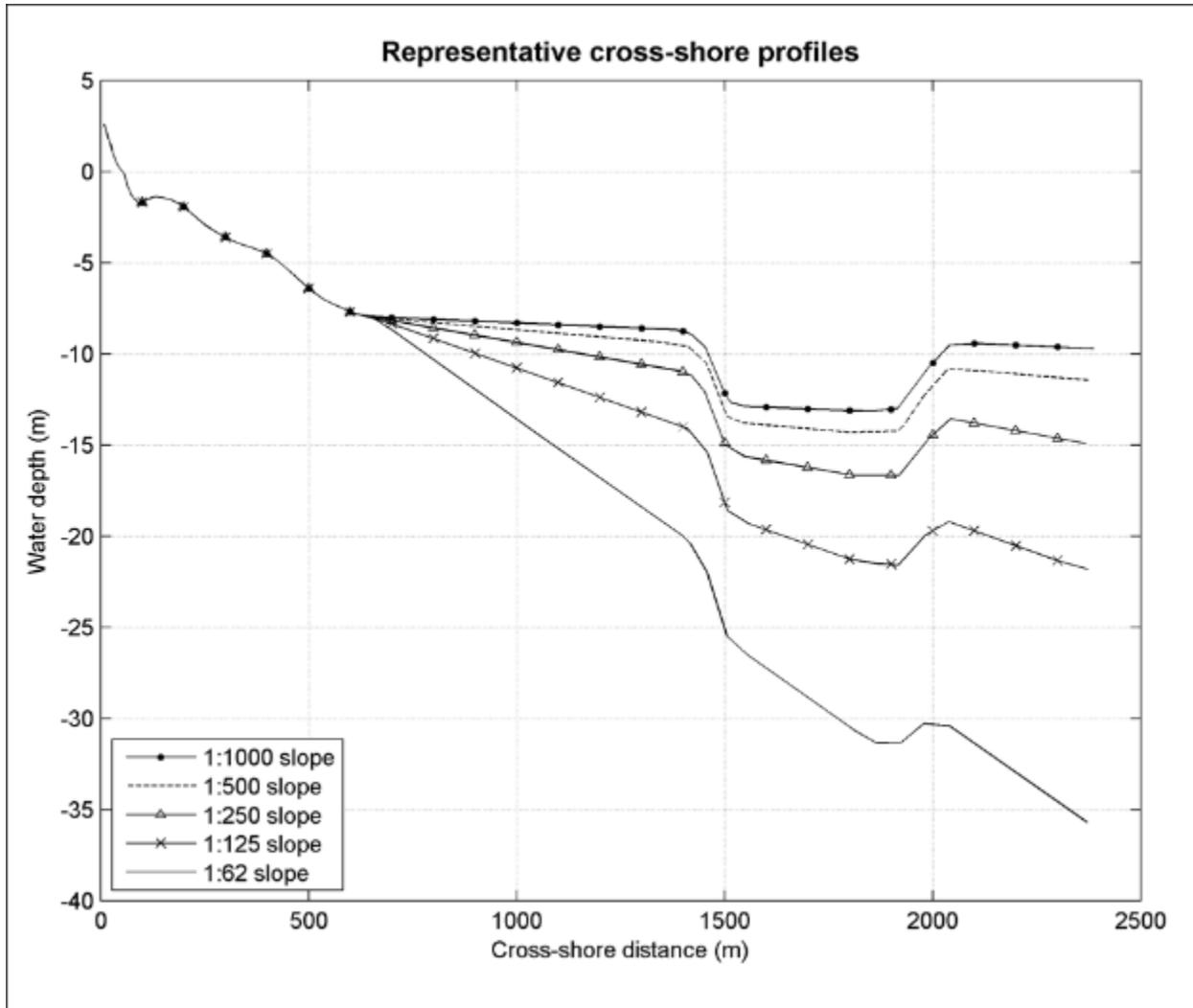


Figure 5.6. Representative cross-shore profiles from the different bathymetric (seafloor slope) scenarios simulated.

Relative beach-volume changes associated with the different bed slopes and water depths were computed using the annual wave climate and are shown in Figure 5.7. Dredge pits located at water depths of 8 m to 9 m (1:1000 slope), 10 m to 11.5 m (1:500 slope) were associated with beach volume changes in the range of +300 m³/m and -250 m³/m (Figure 5.7). Dredge pits located in water depths of 20m to 30m (1:62 slope) showed comparatively smaller effects, in the range of +100 m³/m to -100 m³/m. Because the dominant wave energy was from high-angle wave bands from the left (see Table 5.1), impacts on the adjacent coast were more prominent on the right-hand side of the accretion zone (the downdrift segment). For reference purposes, the dredge pit was located between grid lines 75 and 105 in Figure 5.7. The short-period and lower-energy waves from the right did not cause large effects on the adjacent beach, and the beach response signature

was completely dominated by longer-period and higher-energy NW waves. Because the direction of the mean wave-energy flux was from left to right, areas of erosion/deposition were shifted downdrift. The downdrift erosion zone occurred between 1.5 and 2 km downdrift of the right edge of the dredge pit.

Small changes in the bed slope and in the water depths (approximately 2 m) did not dramatically affect the magnitude of adjacent beach-volume changes caused by the pit. However, larger bed-slope increments, resulting in 5 m of deepening (i.e. from 15 m to 20 m) had pronounced effects on adjacent beach volume changes caused by the pit.

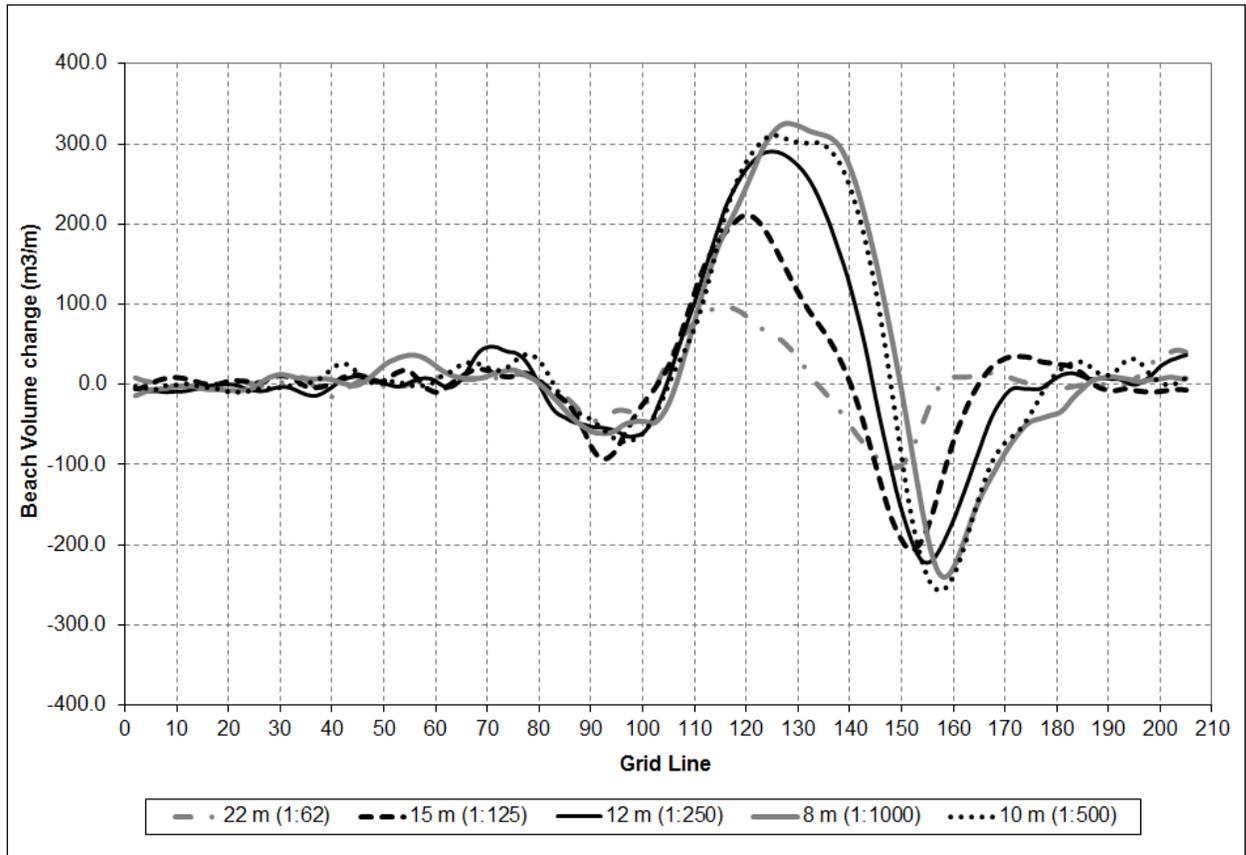


Figure 5.7. Relative beach volume changes, as a function of water depth in dredge pit location. Simulations used an annual wave climate as shown in Table 1. Morphological changes were simulated for a period of 30 days with constant wave forcing. The dredge pits shape was 400 m cross-shore by 800 m alongshore, 4 m depth of cut and a volume of approximately $1.3 \times 10^6 \text{ m}^3$.

5.3.4 Dredge Pit Distance from Shore

In an effort to evaluate the effect of pit distance from the shore, the morphologic model grid was extended to 20 km alongshore and 9 km cross-shore. In that model, the profile reached the depth of 12m at about 1.5 km from the shore, and a platform was created from there on, maintaining a depth of 12 m from 1.5 km to 9 km from the shore (Figure 5.8). The effect of pit distance from shore was evaluated by isolating other parameters and using a pit in 12 m of water depth (flat platform), with dimensions of 400 m cross-shore by 800 m alongshore, a 4 m depth of cut, and a volume of $\sim 1.3 \times 10^6 \text{ m}^3$. The dredge pit was situated 1.7 km, 2.7 km, 4 km, 6 km, and 8 km from

shore, whereas the other parameters (depth of cut, water depth, and dimensions) were kept constant. Relative beach-volume changes for different dredge pit distances from shore, using the annual wave climate, are shown in Figure 5.9. Effects on nearshore volume change ranged from +300 m³/m to -300 m³/m for the shorter distance (1.7 km) to +150 m³/m to -75m³/m for the longer distance (8 km) (see Figure 5.9).

As anticipated, dredge pits located further from the shore produced smaller impacts than did those pits located closer to the shore (Figure 5.9). However, the location of the borrow area impact, the impact signature, shifted further downdrift as the borrow area was pushed farther offshore. This downdrift shift was likely due to the oblique wave incidence because dominant wave energy was from left to right in the study case.

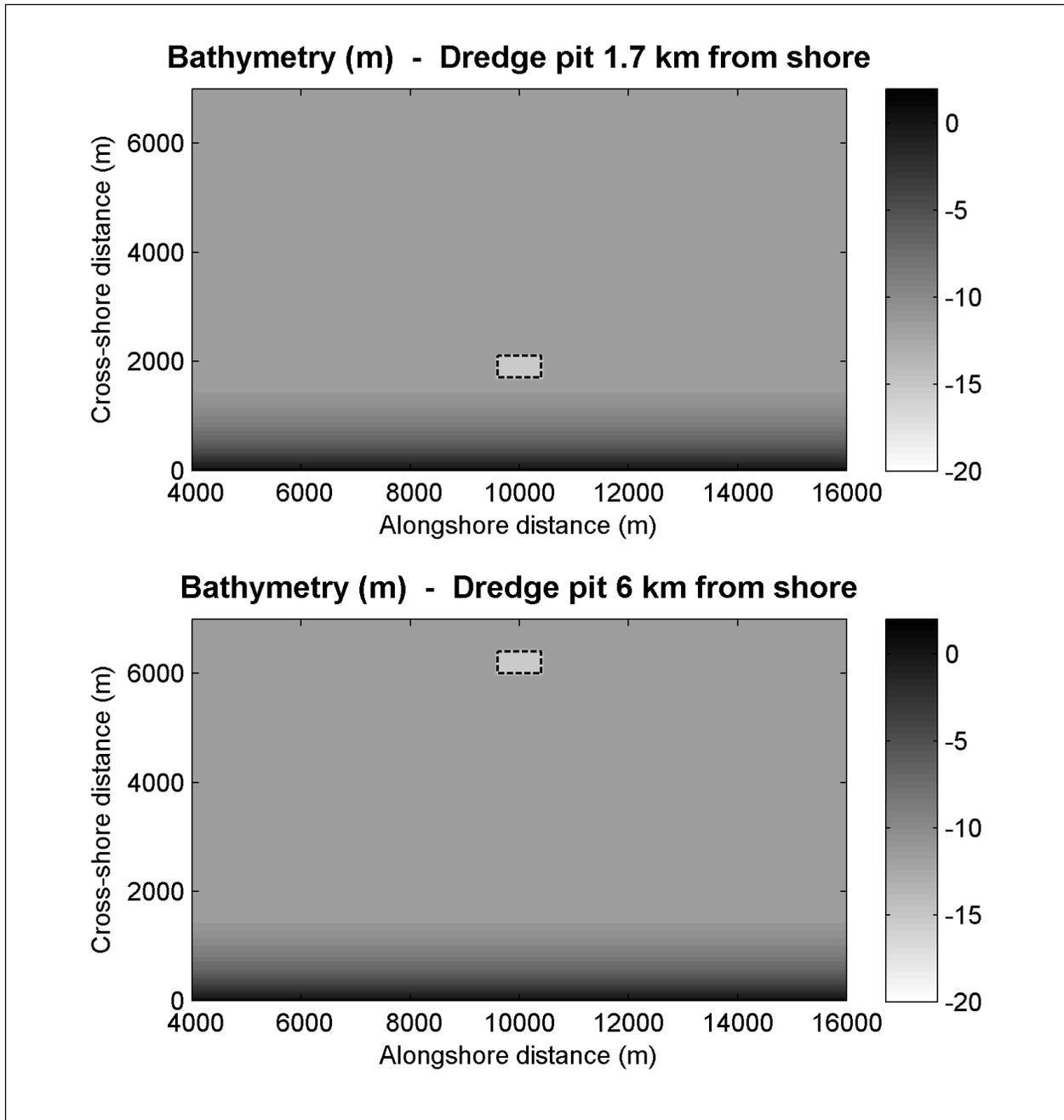


Figure 5.8. Example of dredge pit scenarios with different distances from shore. The borrow pit in the upper panel is located 1.7 km from shore while the pit in the lower panel is located 6 km from shore.

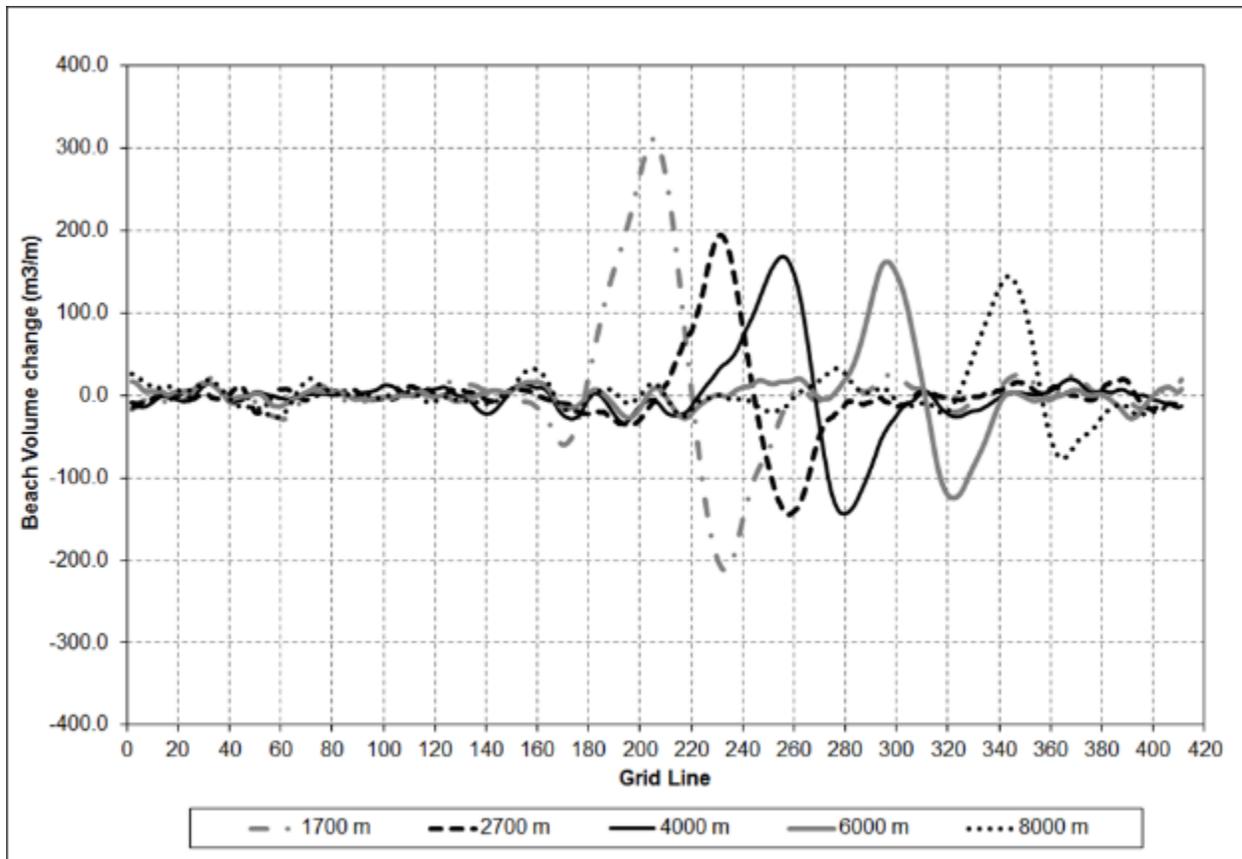


Figure 5.9. Relative beach volume changes, as a function of dredge distance from shore. Simulations used an annual wave climate as shown in Table 1 and morphological changes were simulated for a period of one year. The dredge pits simulated were located in 12 m of water depth (shoreward edge), a 4 m depth of cut, and a volume of $1.3 \times 10^6 \text{ m}^3$.

5.4 DISCUSSION

5.4.1 Implications to the Design of Nearshore Dredge Pits

Dredging nearshore pits in the seafloor is likely to cause zones of erosion and accretion on adjacent beaches. As described by Benedet and List (2008a,b), because of dredging, the flows and the sediment transport potential gradually decrease toward the wave shadow zone, causing a depositional zone, and gradually increase again toward the non-sheltered zone, causing downdrift erosion until the shear stress increases and flow velocity is stabilized, and consequently, the alongshore sediment transport system is reestablished.

This work demonstrates that it is possible to reduce the effects of dredging interventions on adjacent shores by refining the dredge-pit design during project development. Results shown here indicate that, if minimal impacts on the beach are desired, the optimal design configuration is a shallow dredge pit cut that is elongated in the alongshore direction with a narrow cross-shore width (alongshore to cross-shore ratio of 4:1 or greater). These types of long, shallow cuts can be efficiently dredged by hopper dredges.

Long, shallow dredge-pit cuts perform better in terms of nearshore impacts than do cuts that are wide in the cross-shore direction and deeper. This happens because waves “feel” the cut for less time when the pits are narrow in the cross-shore direction, and they refract less when cuts are shallower because of the lesser friction through the bottom of the cut (and, consequently, accelerate) in relation to the original seafloor. The regional bed slope, water depth, and distance of the dredge pit from the shore are also important in the magnitude of the effects on adjacent shores. In general, pits in deeper water produce fewer effects, and greater water depths should be sought when possible and economically/technically feasible. Because of oblique wave incidence in the wave climate used in this case study, the parameter distance from shore affected not only the magnitude of the impacts but also the geographic location of the impacts. Water depth and magnitude of impacts have an inverse relationship because of the widely appreciated fact that waves, especially short waves, interact less with the bottom at greater water depths (Dean and Dalrymple, 1991). In theory, borrow sites at different distances from shore, but situated at same water depths and with the exact same design, would produce similar effects on incoming waves. That is true for the area near the dredge pit; however, as irregular waves travel away from the pit, wave diffraction and wave–wave interactions reduce the effects of the pits on the incident waves.

The methods applied in this article provided additional insight into dredge pit design and can be used by practitioners in the design and permitting of dredge pits around the world. The results, although generalized, will vary from site to site according to the seafloor and wave climate characteristics at each location.

5.5 CONCLUSIONS

Human interventions on the coast that affect wave propagation patterns along the shoreline (wave shadow and focusing zones), such as dredging a nearshore pit, will likely cause zones of erosion and accretion on adjacent beaches. They lead to adjustments of the planforms of the beaches situated in the area affected by the dredging intervention. Some areas of the coast, usually native wide beaches, are not negatively affected by fluctuations in the beach configuration (additional erosion and deposition). Heavily urbanized coasts or sensitive environments protected by narrow beaches can, however, be severely affected by such fluctuations. This study shows that it is possible to reduce the unwanted effects from dredging interventions on the adjacent coast. Results shown here indicate that by maintaining similar dredge volumes, dredge pit designers can reduce by half the unwanted impacts on adjacent shores by manipulating dredge pit design parameters, such as cut depth, the cross-shore width of the pit, and, if the sand reserve is large enough, by increasing the distance from the shore and the water depth. Nonetheless, the optimum pit design may be constrained by additional issues, such sediment availability, feasibility of extraction, cost of extraction, as well as many environmental restrictions. A dredge pit that has a long, parabathic extent and a narrow, diabathic extent, with a shallower depth of cut, produces fewer nearshore impacts than does a dredge pit that has a wide, diabathic extent with a deeper cut depth. Based on these results, designers should favor shore-parallel, shallow, long, and narrow pits whenever possible in lieu of deeper cuts with wider cross-shore extent.

The regional bed slope, water depth, and distance from shore are also important in the magnitude of the dredge pit impacts on adjacent shores. In general, pits in deeper water produce fewer effects, and greater water depths should be sought when possible and economically and

technically feasible. Distance from shore affects not only the magnitude of the impacts but also the location of the impacts in areas with oblique wave dominance. Effects from pits 6 km from shore can be found 4 km downdrift of the pit under oblique wave dominance. This suggests that, if there is enough area, the impacts can be “targeted” to occur in less-sensitive beach segments.

However, the costs associated with dredging are influenced by the distance of the dredge pit from the shore; longer transportation distances generally result in increased dredging costs. Because costs are one of the main concerns when designing a beach-nourishment project, a cost analysis is usually also considered during the process of defining the location and dimensions of the dredge pit.

Dredge pit impacts are not only formed by erosion but also by beach accretion. Wave manipulation to create beach accretion may be unintentional, as is the case for most dredge pits, but it can also be created intentionally for shore-protection purposes in small, localized areas, similar to what is done using artificial submerged reefs. Note, however, that, adjacent to the accretion, there will always be erosion zones because of increases in sediment transport potential from the accretion zone (the area protected from waves) to the wave-exposed zone, and therefore, projects must be evaluated as to whether the erosion forecasted can be tolerated without detrimental effects.

With the recent advances in morphological modeling, the magnitude and geographical locations of beach erosion and deposition zones can be estimated for nearshore dredging projects. Sensitive model tests can provide valuable information about how different dredge pit designs will interact with the adjacent shores. With such insights, possible adjustments to the design of these features can be made, to develop optimized pit designs that minimize downdrift impacts.

CHAPTER 6. A MORPHOLOGICAL MODELING STUDY TO COMPARE DIFFERENT METHODS OF WAVE CLIMATE SCHEMATIZATION AND EVALUATE STRATEGIES TO REDUCE EROSION LOSSES FROM A BEACH NOURISHMENT PROJECT

Abstract

Beach nourishment on open ocean beaches not bounded by headlands or other structures suffers from high rates of lateral losses of fill volume as the nourished shoreline equilibrates with its surroundings. Estimates of lateral losses are essential for beach nourishment design, these predictions have been made in the last decade utilizing empirical formulations, one line models or lately, process-based coastal morphology models. Coastal morphology models are, however, complex and computationally intensive and in order to maintain a balance between model complexities, computational effort and processing capacity, schematization of model input (input reduction) is necessary. This chapter is divided into two main sections. In the first section techniques of wave input reduction for morphological models are evaluated with focus is on open ocean wave-dominated coasts. Subsequently, the optimized morphological model is applied to evaluate coastal engineering interventions aimed at reducing volume losses from the Delray Beach Nourishment Project. Wave input reduction is defined here as the process of reducing the full wave climate of a given coastal region to a set of representative wave-wind conditions, ‘running’ a model with these representative wave conditions in sequence for a smaller time period (i.e. a few tide cycles) and multiplying its effect on the morphology by a morfac value, that is related to the frequency of occurrence of that wave condition in nature, or its weight in the overall wave climate. Five different techniques of wave input reduction were tested. Of all the methods of wave climate schematization tested the methods defined as ‘Energy Flux Method’ and ‘Opti Method’ showed best results in terms of representing accurately the sediment transport patterns of the study area. The tests conducted indicate that a number around 12 representative wave cases was enough to represent an annual wave climate compared to a very detailed wave climate used as benchmark. The optimized model was used to evaluate alternative engineering solutions to reduce volumetric losses from the beach nourishment project. Engineering solutions evaluated included a construction of a breakwater field, backfilling all dredge pits located offshore of the project site, construction of a groin field at the downdrift end of the project, and backfilling the deepest dredge pit. These engineering interventions caused a reduction in beach volume losses within the project limits with varying levels of effect on the downdrift beaches. Reduction of the volume loss from the project site is technically feasible and may be economically feasible pending further economic feasibility evaluation.

This chapter is based on the following publications:

Benedet, L., Dobrochinski, J.P.F., Walstra, D.J., Klein, A.H.F., Ranasinghe, 2015*. *A Morphological Modeling Study to Compare Different Methods of Wave Climate Schematization and Evaluate Strategies to Reduce Erosion Losses from a Beach Nourishment Project. Submitted to Coastal Engineering.*

6.1. INTRODUCTION

Beach nourishment is the preferred method of coastal protection in the U.S. mainly because it preserves the aesthetic and recreational values of protected beaches by replicating the protective characteristics of natural beach and dune systems. The U.S. has more than 200 nourished areas and since the 1920s has placed more than half a billion cubic meters of sediments on its beaches (Benedet and Campbell, 2004).

Beach nourishment projects conducted on open ocean beaches not bounded by headlands or other structures suffers from high rates of lateral losses of fill volume as the nourished shoreline equilibrates with its surroundings (*i.e.* Dean and Yoo, 1992). In order to reduce volumetric losses, thus increasing the interval of subsequent nourishments and reducing beach nourishment costs, engineering solutions can be designed and implemented. These engineering solutions can be classified in two macro-categories: (1) interventions to the incoming wave climate such as modifications to the offshore bathymetry or breakwaters aimed at reducing alongshore transport rates or (2) introduction of physical barriers to alongshore sediment transport such as groins.

Engineering interventions to reduce fill lateral losses, however, may impact downdrift shorelines therefore there is a fine balance between the amount of sand retention desired and the occurrence of downdrift erosional impacts. In the past such fine balance has been sought by analytical solutions such as Dean and Yoo (1992), 1D line models (Hanson and Kraus, 1989) or trial and error (*i.e.* construction of temporary structures and annual monitoring). In this work this fine balance between sand retention and downdrift impacts is evaluated utilizing a process-based morphological model. Initially, in order to simulate the beach nourishment behavior and the effects of engineering interventions efficiently, a detailed analysis of wave climate schematization methods is conducted. Subsequently, the model setup that exhibited best agreement against a benchmark is utilized to evaluate coastal engineering interventions aimed at reducing volume losses from the Delray Beach Nourishment Project.

Numerical models of coastal morphology simulate a range of coastal processes (*i.e.* wave generation and transformation, coastal circulation, sediment transport) and use the principle of conservation of mass to calculate coastal morphology changes. In these models, specific input forcing such as water elevation, discharge and wave conditions are prescribed at the boundaries in order to simulate the above mentioned processes over the model domain. Specific input reduction techniques were developed over the last few years to enabled simulations of morphological evolution of coasts over timescales of years to decades efficiently (Stelling *et al.*, 1999, Roelvink and Reniers, 2012, Lesser, 2009, Brown and Davies, 2009, Walstra *et al.*, 2013).

The computational effort required by morphological simulations of time periods greater than 1 year and the amount of information generated by these models is much larger than traditional hydrodynamic models. This is due mostly to the number of additional processes involved in morphological simulations and the numerical grid resolution needed to resolve processes such as surf-zone sediment transport and interactions between morphological change and coastal structures. Furthermore, as computational power evolves, model complexities also increase, so that computational time remains about constant. Coastal morphology models, for example, are getting increasingly more complex with the use of full baroclinic 3D models with 10 to 30 vertical computational layers, multiple sediment fractions (horizontally and vertically), interaction between physical and ecological processes and more sophisticated model formulations. In order to

maintain a balance between model complexities, computational effort and processing capacity, schematization of model inputs (input reduction) is necessary.

Techniques of wave input reduction for morphological models are evaluated in detail in this work in order to develop an efficient morphological model of the study area, an open ocean wave-dominated coasts. Even though the overall principle is similar, the techniques used to reduce the full range of wave conditions to a set of representative conditions can vary greatly, so can the number of representative conditions selected, the total ‘weight’ applied to each wave condition and the chronology of wave events. All of these variables have direct implications to the quality of model results. In this paper six different techniques of wave input reduction are tested using Delray Beach, situated in SE Florida, as a case study. These techniques are compared against each other and against a benchmark in order to evaluate the accuracy of each technique and to provide recommendations for coastal morphological modeling studies in wave-dominated coasts.

The numerical model setup with a wave climate that showed the best fit against the benchmark is used to investigate coastal engineering interventions designed to reduce sand volume loss from the Delray Beach nourishment project. Alternatives evaluated include removing all the offshore dredge pits by sediment re-filling, re-filling the deepest dredge pits identified as the main causes for the erosional hot spot by Benedet *et al.* (2013) at the south end of the nourishment project, adding a breakwater field consisting of three breakwaters at the south end of the nourishment project and lastly adding a groin field consisting of three groins at the nourishment’s downdrift (south) end.

6.2. STUDY AREA

The study area, Delray Beach, is located in the southeast coast of Florida, USA. The continental shelf in front of Delray Beach is relatively short and steep. Depths up to 200 m are found in a distance of just 9 km from the coast. The coastline is straight and aligned in the N-S direction. Coastal morphology changes at Delray Beach are controlled by natural and man-induced bathymetry anomalies located offshore (Benedet et al., 2006, 2007; Benedet & List, 2008; Hartog et al., 2008) (Figure 6.1). The beach contains beach survey stations at approximately every 300 m, which are surveyed annually. These survey stations are normally known as beach profile monuments, and are labeled as ‘R’ monuments, after the former Florida Department of Natural Resources (now FDEP, or Florida Department of Environmental Protection). The study area described in this paper extends from R178 to R190, with focus on the area between R180 and R188, the limits of beach fill placement.

The beach was initially nourished in July 1973 with the placement of 1,250,000 m³ of sand. It was subsequently fully renourished with volumes ranging from 800,000 m³ to 1,000,000 m³ in 1978, 1984, 1992, 2002 and 2013. There was also a smaller nourishment (250,000 m³) to respond to episodic hurricane-driven erosion in 2005. The nourishment project of 2002 was executed just before the acquisition of the bathymetry data used in this work. In the 2002 project about 940,000 m³ of sand were deposited in a length of 3,000 m of beach, or 313 m³ per linear meter of beach. This sand was placed between the monuments R180 and R188 (see Figure 6.1 for monument locations).

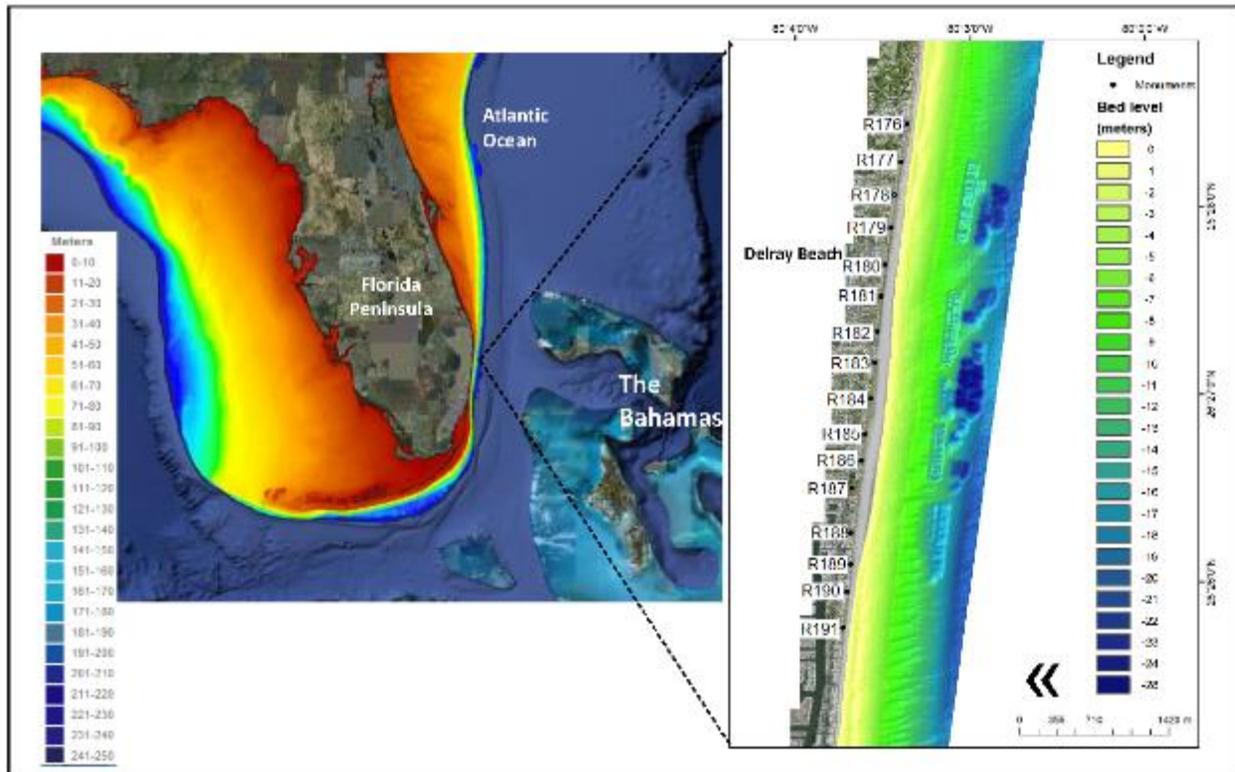


Figure 6.1. Study area location and overall bathymetry, elevations are referenced to the NAVD 88 vertical datum.

Previous studies indicate that volume changes at Delray Beach varies greatly in the alongshore direction (Benedet *et al.*, 2007). The beach width in R178 (just north of the beach fill project) is relatively stable and wide, the beach extension between R184 and R185 is classified as a cold spot (a stable or accretion zone) and there are trends of erosion both in north and south sides of this cold spot. In the region between R186 and R187 the erosional trend is more pronounced, being considered a prominent hot spot of erosion. This zone extends for approximately 600 m alongshore. About 50% of total erosion losses from the project area occur within this erosional hot spot (Benedet *et al.*, 2007).

6.3. NUMERICAL MODEL SETUP

A process based numerical model of coastal morphology developed by Deltares in close cooperation with Delft University of Technology (Delft, The Netherlands), is used in this study (WL Delft, 2007a, b, c, Lesser *et al.*, 2004), the model is commonly known as Delft3D.

The Delft3D model is a process-based model containing a detailed description of relevant processes such as waves, tide, currents and sediment transport and the interaction with each other. This interaction may cause a varying flow field and bed level changes. The Delft3D-online module performs the hydrodynamic computations and simultaneously (“online”) calculates waves, transport of sediments and updates the bathymetry.

The model makes use of the SWAN (Simulating Waves Nearshore, HOLTHUIJSEN *et al.*, 1993) model for the WAVE-module. The mean wave directions are computed by the wave model SWAN after which the energy associated with the waves propagating shoreward is computed.

The FLOW-module provides the hydrodynamic basis for many cases in coastal environments. In LESSER et al. (2004) a detailed description is given of the online version of the FLOW-module and its applications. The FLOW module is a hydrodynamic flow simulation program that simulates transport phenomena and solves the unsteady shallow-water equations in 2DH (depth-averaged) or 3D. In the module phenomena as tide, wind and wave driven flows, stratified and density flows are included in situations where bottom level, water level and velocity field change significantly during a flow simulation. Recent modifications in the FLOW module included three dimensional wave effects as wave-induced mass flux, wave-induced turbulence, streaming and forcing due to wave breaking (WALSTRA et al., 2000).

For sediment transport a new approach has been implemented. Instead of using the modules Delft3D-SED and -MOR the sediment online version continuously updates transport of sediments and therefore is possible to change the bed level and give feedback to the hydrodynamics at every hydrodynamic timestep. This approach allows the simulation of feedback processes between hydrodynamics and sediment response (morphodynamics), making the ‘online’ sediment version of Delft3D especially useful for investigation of sedimentation and erosion problems in complex coastal situations (Lesser et al., 2004). For the transport of sediments two types of sediment transport are computed. Over the entire water column the suspended sediment is computed and for a reference height above the bottom the bed load transport is computed. The sediment transport module uses the approximation method of VAN RIJN (1993).

Morphodynamic development time scales are significantly larger than those of hydrodynamic time scales. The morphological acceleration factor (Morfac) is therefore used so only for a fraction of the duration the hydrodynamic simulations are required. In this way the speed of changes in the morphology is scaled up to a rate where it begins to have a significant impact on the hydrodynamics and the computational time can be reduced.

The simulations conducted in this work focused on the representation of alongshore transport patterns, therefore the model was set up as a depth-averaged (2DH) model. The input data of the wave conditions propagated in this work consist of parametric wave data of significant wave height (H_s), peak period (T_p), peak direction (Dir_p) and directional spreading. The model uses a Jonswap type spectrum with the peak enhancement parameter of 3.3. The directional distribution is a function of the wave period, and it is expressed as the Cosine power.

Model parameters (bottom roughness, sediment transport, morphology update parameters etc.) used in this work were the same as used in other modeling studies of Delray Beach conducted by the authors (Benedet and List, 2008, Benedet et al., 2007, Hartog et al., 2008). These parameters included a wave bottom friction of $C_{JON} = 0.067 \text{ m}^2\text{s}^{-3}$, the default Chezy bottom roughness in the flow module of $65 \text{ m}^{0.5}\text{s}^{-1}$ and sediment transport parameters $SUS = 1$ and $SUSW$ and $BEDW = 0.1$. The morphological model results for the selected wave climate were calibrated in terms of volume changes to observed volume changes at Delray Beach.

6.3.1. Wave Climate

The wave data used in this study is a parametric time series covering the period between March 2002 and June 2004, obtained for a location in deep water adjacent to Delray Beach. The information in the data series is significant wave height (H_s), peak period (T_p) and wave direction, with a temporal resolution of three hours. This data is result of the hindcast model WavewatchIII

(Tolman, 2002). The WavewatchII data was extracted from a grid point located directly offshore of the project site in approximately 200 m of water depth.

The time period of the wave data time series analyzed and used in this work extends from March of 2002 and June of 2004, concurrent to beach profile surveys used in the comparisons between modeled and observed beach changes. Most frequent waves approach the coast from the E-SE, with height lower than 0.5 meter and periods, for the most part, between 6 and 8 seconds (Tables 6.1 and 6.2).

High energy waves from NE and ENE are observed (tables 6.1 and 6.2). These waves have a longer period (swell conditions) and are related with frontal systems (cold fronts) that occur during winter months. Waves coming from directions between N and E are dominant in frequency and energy. In terms of percentage, 89% of the wave conditions have height lower than 1.5 meter and about 93% of the waves have peak periods lower than 10 seconds, demonstrating that study area is exposed to relative calm wave conditions for most of the time.

A window of wave directions that propagate towards the shore (between 26 and 166 degree) and affects directly coastal behavior was considered for the wave climate schematization work reported in later sections of this paper. Additionally only waves above 0.5 m were considered during wave climate schematization. This 0.5 m threshold was adopted because in earlier sensitivity model runs conducted by the author (Benedet et al., 2006, 2007, Benedet and List, 2008) show that waves smaller than 0.5 m do not produce significant morphological change in the study area.

Table 6.1. Incoming wave direction versus Hs bivariate histograms for the period between March of 2002 and June of 2004. The shaded cells highlight the wave classes with higher frequencies of occurrence.

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	TOTAL
4 - 4.5																	
3.5 - 4			0.06														0.06
3 - 3.5	0.06	0.22	0.12														0.40
2.5 - 3	0.12	0.40	0.35	0.38													1.25
2 - 2.5	0.50	0.67	0.70	0.69	0.10											0.03	2.70
1.5 - 2	1.07	1.60	1.29	1.26	0.67	0.01	0.04								0.01	0.22	6.18
1 - 1.5	2.04	3.30	4.44	5.16	3.19	0.69	0.22	0.18	0.13	0.12	0.01		0.19	0.26	0.44	0.95	21.32
0.5 - 1	2.96	2.61	7.93	9.32	10.79	3.81	1.96	1.69	0.53	0.31	0.34	0.47	0.40	0.47	0.57	0.95	45.09
0 - 0.5	0.76	0.79	1.69	2.89	12.21	1.63	1.20	0.56	0.21	0.23	0.12	0.15		0.01	0.29	0.28	23.01
TOTAL	7.50	9.58	16.57	19.70	26.96	6.14	3.43	2.42	0.86	0.66	0.47	0.62	0.59	0.75	1.32	2.43	100.0

A reference wave climate was developed utilizing the Wavewatch III data. This reference wave climate is used as a benchmark to compare wave schematization methods used in this work. The reference wave climate consists of a very detailed wave climate made up of 65 equidistant representative wave cases (Figure 6.2). To develop the wave climate a number of wave classes were created by dividing the wave time series into specific wave height (Hs) and wave direction intervals (Figure 6.2). The intervals used are 0.4 m for Hs and 10° for wave direction. Each class is represented by the black solid lines in Figure 6.2. For each class, a representative sea state is calculated, where the significant wave height, peak period and incoming direction are the mean

values found in the wave class. The representative sea state for each class is represented by the dots in Figure 6.2.

Table 6.2. Incoming wave direction versus Tp bivariate histograms for the period between March of 2002 and June of 2004. The shaded cells highlight the wave classes with higher frequencies of occurrence.

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	TOTAL
16-18																	
14-16			0.03														0.03
12-14			0.56	0.23	0.42												1.22
10-12		0.66	2.32	1.73	0.31												5.01
8-10	0.09	2.48	5.80	6.43	5.11												19.92
6-8	3.66	3.97	5.64	8.09	15.39	0.51	0.16	0.06	0.09							0.40	37.97
4-6	3.46	2.37	2.04	3.03	5.23	4.75	2.20	1.10	0.34	0.29	0.01	0.06	0.22	0.37	1.00	1.88	28.34
2-4	0.29	0.10	0.19	0.18	0.50	0.88	1.07	1.26	0.44	0.37	0.45	0.56	0.37	0.38	0.32	0.16	7.52
TOTAL	7.50	9.58	16.57	19.70	26.96	6.14	3.43	2.42	0.86	0.66	0.47	0.62	0.59	0.75	1.32	2.43	100.0

Each wave class is simulate by a few tide cycles and multiplied by a morphological scaling factor, ‘morfac’, to represent its frequency occurrence in a full year. The morfac increases the depth changes after each hydrodynamic time step by a defined spatially-constant factor defined as the ‘morfac’ (Lesser, 2009, Ranasinghe *et al.*, 2011). For example, a simulation over one tidal cycle (12 hours) with a morfac of 10 actually represents 120 hours of morphological change. With the use of the morfac, in combination with wave-wind and tide input reduction techniques discussed in this paper, the time required to perform simulations of morphology changes over time periods of years to decades can be reduced drastically.

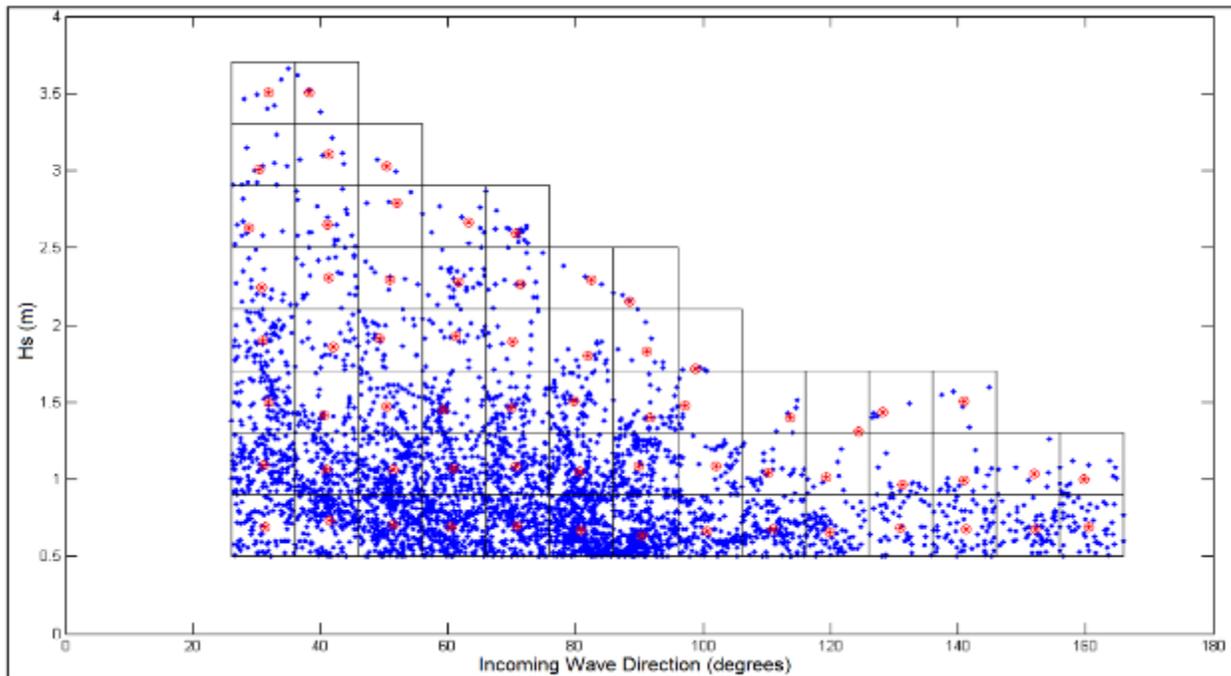


Figure 6.2. Representation of the wave classes and representative sea states used in the robust wave climate. Each square represents a wave class and the dots inside each square are the average sea state used to represent each wave class in the numerical model.

6.4. METHODS OF WAVE CLIMATE SCHEMATIZATION

A wave climate is ‘schematized’ in longer term morphological simulations (>1yr) to reduce size of the set of wave conditions needed to run the model. This is done to optimize the model computationally (speed up simulations) and also to facilitate post-processing and evaluation of model results. It is possible to evaluate the influence of each wave condition in a year of morphological change when you have a dozen or so wave records to analyze but difficult to do so when you have 2,000+ wave records.

Five different methods of wave climate schematization are tested in this work, they are named: ‘Fixed Bins Method’ (FBM), ‘Energy Flux Method’ (EFM), ‘Energy Flux with Extreme Wave Conditions Method’ (EFEM), ‘CERC Method’ (CERC) and ‘Opti-Routine Method’ (Opti). Four of these methods are directly based on the wave climate characteristics. The Opti-Routine method is based on transport patterns resulted from modeling simulations.

Results of the different wave schematization methods are compared with the results produced by the benchmark (reference wave climate) consisting of a detailed wave climate. The performance of a particular method of wave climate schematization is judged to be superior to other methods when its results are closer to the benchmark.

6.4.1. Criteria used to Define Wave Classes in the Different Methods of Wave Climate Schematization Evaluated

In general, wave schematization methodologies consist in dividing a wave time-series into directional and wave height classes, and calculating a representative sea state for each class. The difference between these methods, however, is the criteria used in the definition of the wave classes and the representative sea state. In this work, all the five methods are used to reduce the full wave climate to 30, 20, 12 and 6 representative wave cases. The upper and lower thresholds for the number of wave cases were defined based on sensitivity tests conducted by the authors that demonstrated minimal improvements in model performance with a number of wave cases >30 and abrupt deterioration of results when the number of wave cases drops <6.

To develop the wave climate utilizing the FBM, EFM, EFEM, CERC wave climate schematization methods the following steps were performed utilizing specific the criteria established by the method:

- (1) A scatter plot of wave height (H_s) vs wave direction is prepared
- (2) The wave time series is divided into a number of wave directional bins.
- (3) The number of wave height subdivisions that each wave direction will be divided into is defined (height bins).
- (4) Wave classes are defined based as a result of ten intersections between the direction and height bins.
- (5) Frequency occurrence and a representative sea state are calculated for each wave class.

This procedure is illustrated in Figure 6.3 for the energy flux method (EFM). In the Opti method, however, the procedure is slightly different since the method utilizes a procedure of automatic trial-and-error Delft3D simulations to reduce a reference wave climate to a subset with

fewer wave conditions while maintaining a similar transport curve as generated by the original reference simulation conducted with a larger number of wave cases. The Opti procedure and the criteria used to define the wave direction and height intervals in the other methods are described in the following sections of this paper.

6.4.2. Fixed Bins Method (FBM) of Wave Climate Schematization

In this method the modeler arbitrarily defines the number of directional intervals and height intervals. Initially a given number of directional bins with fixed degree intervals is used to divide the wave time series and subsequently, a pre-defined number of wave height intervals is applied to each wave directional bin. As a result, directional intervals have the same degree range and each directional bin is divided into the same number of wave height intervals that are fixed, but do not necessarily have the same height range (Figure 6.4a). For example, in the study area the waves approach the shore cover a directional window of 140°. Divided this window by 4 we have four direction bins of 35° intervals each, when these directional bins are divided by, for example, 3 height intervals, the wave height range of each interval will vary in each directional bin according to the distribution of wave heights in each bin (Figure 6.4a).

The total number of wave classes will be equal to the number of wave direction bins multiplied by the number of wave height bins. After the wave classes are defined the frequency of occurrence of each wave class is calculated, which is related to the number of wave cases occurring within each direction and height bin. A representative wave case is then defined for each wave class, where the significant wave height, peak period and incoming direction are the mean values of all the records found within the class, the representative wave case is shown by the dots inside each wave class in Figure 6.4a.

6.4.3. Energy Flux Method (EFM) of Wave Climate Schematization

This method is based on wave energy flux concepts where the energy flux of each wave record from a wave time series is calculated utilizing the following equation:

$$E_f = (\rho g H_s^2 / 8) C_g \quad (1)$$

where ρ is the water density (1025 kg/m³), g is the gravity acceleration (9.81 m/s²), H_s is the significant wave height and C_g is the group wave celerity, in deep water.

Instead of arbitrarily defining the wave directional bins with fixed intervals like in the FBM method, in the EFM method directional bins are calculated as ‘equal energy’ intervals, following equation (1). The wave height bins are also calculated as ‘equal energy’ bins thus the intervals of the wave classes are defined in order to create wave classes with the same final sum of energy flux (Figure 6.3). In this method, for example, if a wave climate is divided into 20 wave classes (5 directions and 4 heights) each wave class contains 1/20 of the total wave energy of ‘E/20’ (Figure 6.3).

As a result, the wave classes that are developed using the EFM (figure 6.4b), when compared to the FBM (Figure 6.4a), have higher resolution and smaller intervals (along both directional and height axes) where there is more wave energy and the opposite (less resolution and larger intervals) where there is less wave energy. The wave case used to represent each wave class is also calculated using the mean energy flux concept. Wave direction is the mean energy flux direction of the bin,

the period is the mean period of the group and wave height is calculated according to the mean energy flux of the bin. An example of a wave climate consisting of 12 wave cases developed using the EFM is shown in Figure 6.4b.

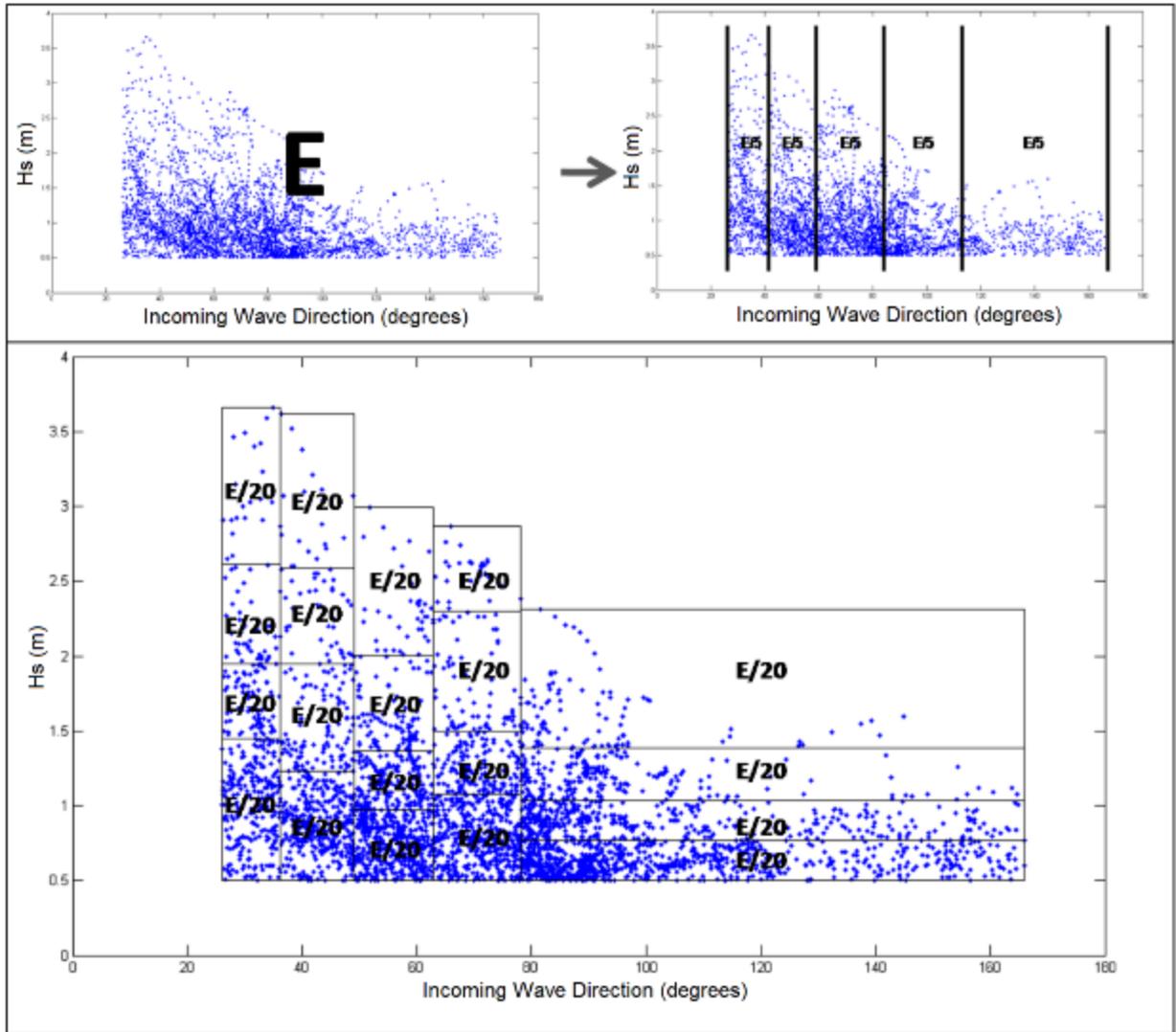


Figure 6.3: Definition of directional bins by the Energy Flux Method with each direction bin contains 1/5 of the total wave energy (upper two panels). Subdivision of each direction bin into height bins is shown in the bottom panel. The result is the division of the wave record into twenty wave cases (4 directions and 4 heights) with each wave class containing 1/20 of the total wave energy of the record. Solid lines represent each wave class and small dots represent wave records that fall within each wave class.

6.4.4. Energy Flux Method of Wave Climate Schematization with Extreme Wave Conditions (EFEM)

This method is based on the Energy Flux Method as previously described, however, an extreme wave condition is added to the wave climate in order to provide a representation of a ‘storm condition’ in an averaged wave climate. The extreme wave class contains the 12 wave records with the highest wave energy in each wave directional bin, therefore, in this method, there is always one extreme wave case per directional bin. The difference between the EFEM and EFM is that EFEM takes into account extreme events that occur 12 hours per each wave directional bin, that is, we apply the EFM method and superimpose one wave case per directional bin, calculated from the 12 highest waves in the record in each directional bin. These extreme waves represent a small portion of the wave record (low frequency of occurrence), however, can be important to sediment transport patterns and consequently morphology change. An output of this method utilized to develop a wave climate with 12 representative wave cases each is shown in Figure 6.4c.

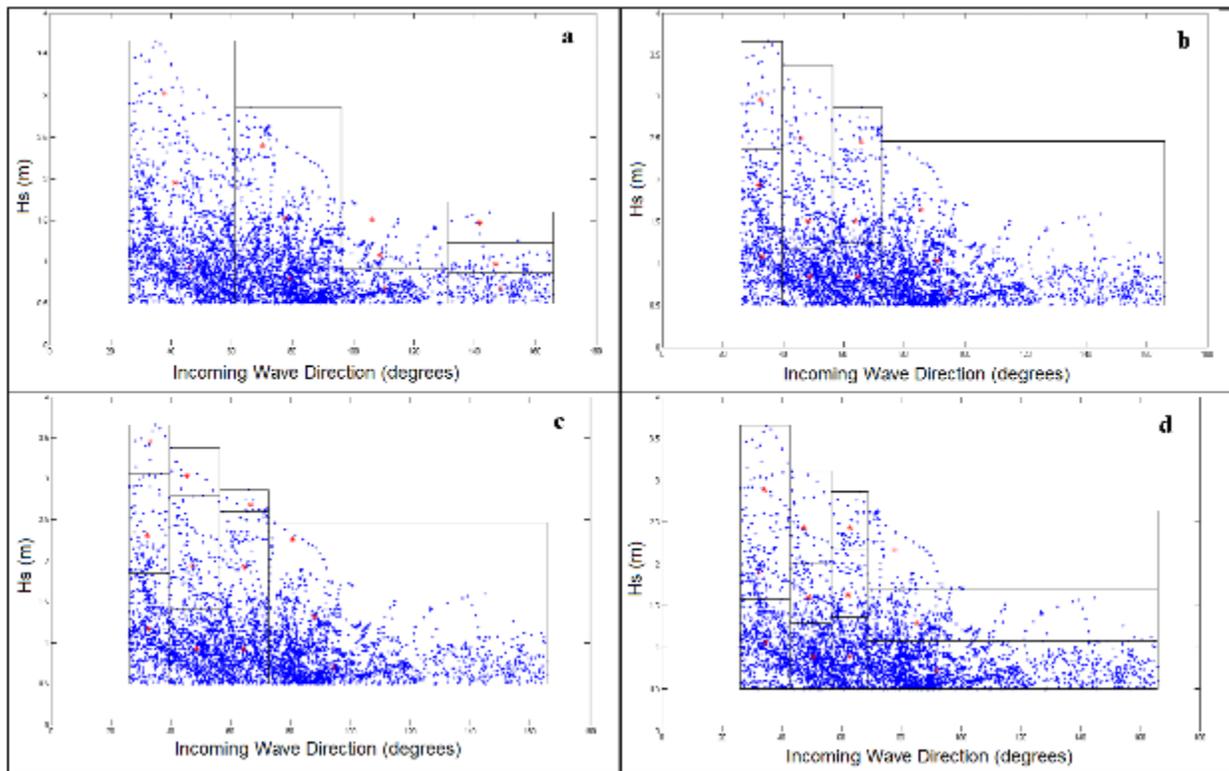


Figure 6.4: In this figure each rectangle is a wave class, small dots are all the wave records contained in the wave class and the large dot is the wave case used to represent the wave class (mean values of H_s and direction in the class). All figures show wave climates comprised of 12 representative wave cases developed utilizing four different methodologies. The output of the ‘fixed bin’ wave schematization method (FBM) is shown in 6.4a, the output of the ‘Energy Flux Method’ (EFM) shown in 6.4b, the output of the ‘Energy Flux with Extreme Wave’ schematization method (EFEM) is shown in 6.4c and the output of the ‘CERC’ wave schematization is shown in 6.4d.

6.4.5. Method of Wave Climate Schematization using the CERC Equation

This method of wave schematization is similar to the EFM however instead of wave energy flux equation it uses sediment transport potential to defined the wave direction and height bins.

Sediment transport potential is calculated with the empirical CERC formula (SPM, 1984). The volume transport of each wave record is obtained by the following equation (SPM, 1984, CEM, 2002):

$$Q_t = K \left(\frac{\rho \sqrt{g}}{16 \kappa^2 (\rho_s - \rho) (1 - n)} \right) H_b^{\frac{5}{2}} \sin(2\alpha_b) \quad (2)$$

where ρ is the fluid density (1025 kg/m³), g is the gravity acceleration (9.81 m/s²), κ is the breaker index defined by H_b/db (0.78), ρ_s is the sediment density (2650 kg/m³), n is the porosity (0.4), H_b is the significant wave height in break point, α_b is the wave breaker angle relative to the shoreline and K is a constant used as a calibration coefficient.

The principle of the method is to define wave classes that represent similar accumulated potential longshore sediment transport. The direction and height bins are calculated as ‘equal transport’ intervals. As the final output, in a wave climate with n wave classes each wave class will contain $1/n$ of the potential sediment transport of the entire wave record. Compared to the EFM the CERC Method yields somewhat similar wave classes with small differences (see Figures 4b and 4d) and both use a measure of wave energy as the main parameter (H_s^2 in the EFM method and $H_b^{2.5}$ in CERC). The main difference between these two methods (CERC and EFM) is that the wave direction is considered in the CERC method since the CERC equation is basically the wave energy flux multiplied by wave direction. As a result of the CERC method, waves with breaking angle near 0 or 90 degree relative to the shoreline will induce less transport and be less represented in the resulting wave climate than waves with the same height and breaking angle near 45 degree. An example of a wave climate consisting of 12 representative wave cases is shown in Figure 4d.

6.4.6. Opti-Routine Method of Wave Climate Schematization

This method of wave schematization was based on a code originally written in by D. Roelvink and further refined by Roelvink and others (Lesser, 2009, MOL 2007, Roelvink and Reniers, 2009). The procedures adopted in this method of wave schematization are significantly different than the other methods previously described in this manuscript. For this study the application of the method is based on the following steps:

- (1) A Delft3D simulation with a large number of wave cases (i.e. >50) is conducted and a sediment transport curve is generated. In this work the results of the reference wave climate, with 65 wave cases, was used as input to the Opti routine.
- (2) A procedure of automatic trial-and-error reduces the wave climate to a subset with fewer wave conditions while maintaining the similar transport curve as generated by the original simulation conducted with a large number of wave cases.
- (3) To reduce the wave climate to the subset the Opti routine weights the transport field of each representative wave condition (65 wave conditions in this paper) by the frequency

occurrence of the condition. The wave condition with the lower contribution to the final sediment transport curve is excluded and the weights of the each remaining wave condition (now 64 wave conditions) are redistributed n times to match the target sediment transport curve as best as possible (n is the number of iterations, defined by the user). The combination of weights that reproduce better the patterns of transport are selected and saved.

- (4) The procedure above is repeated so a small subset of wave cases that can represent well the overall sediment transport can be selected. Output of Opti code is the reduced set of wave conditions and adjusted weight factors for each condition (Mol, 2007, Lesser 2009, Roelvink and Reniers, 2011).

The numerical modeler can select the number of representative wave cases that are targeted when applying the Opti method. The RMS errors, bias and covariance of the modified weighted sum of conditions relative to the reference results (reference wave climate) are tracked and plotted as a function of the number of wave cases. When the number of representative wave cases is reduced to only a couple cases (e.g. 2, 3 cases), the error increases. In this case a combination of wave cases with its respective weights that reproduce well the pattern of transport observed in reference model results cannot be found. Usually a number of 6 to 12 wave cases can yield a good representation of the ‘reference results’ using the Opti Method.

An example of a wave climate with 12 wave cases developed using the Opti method is shown in Figure 6.5. The wave classes highlighted in Figure 6.5 (color-filled) are the final wave classes selected by Opti-routine.

In Figure 6.5 it can be noticed that the Opti Method of wave climate schematization favors the selection of the wave classes with more energy. In the study area Opti yield a selection of exclusively waves from NE (longer period swells with higher H_s) rather than short waves from E-SE bands. Also, it is important to notice that when using Opti the modeler needs to be certain that the reference model (model with large number of wave cases used as input to the Opti routine) is representing well the sediment transport patterns that are object of the study.

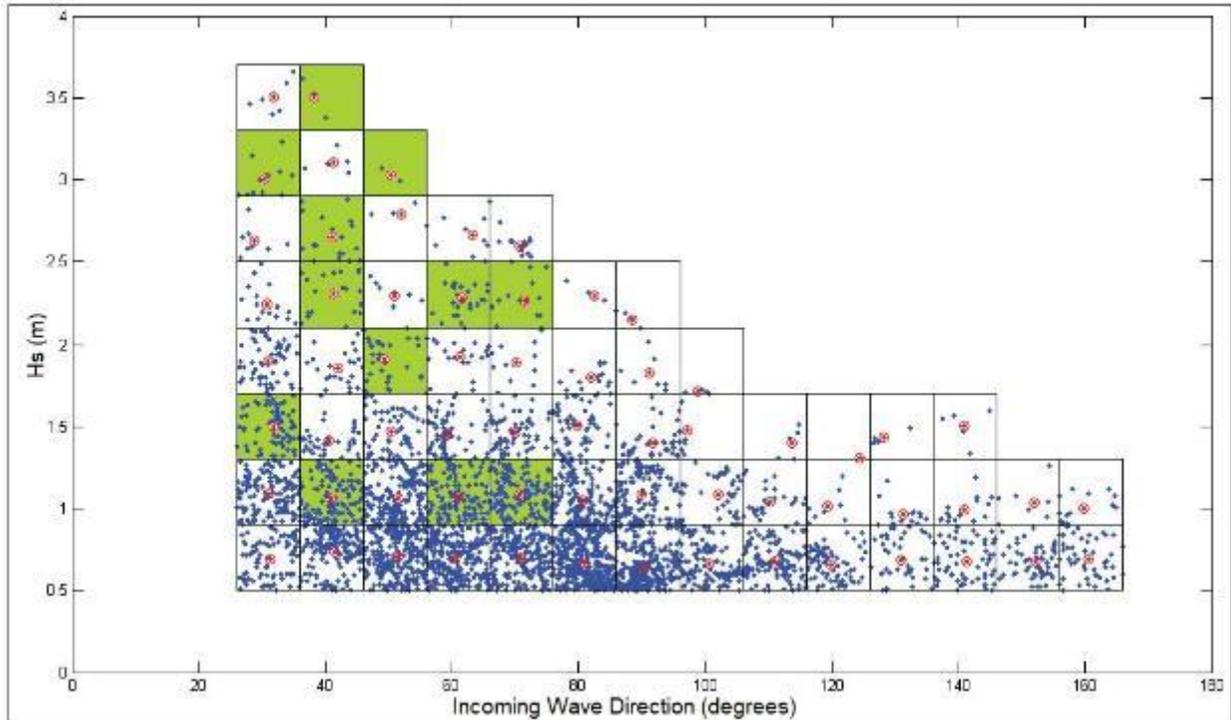


Figure 6.5: Representation of the output of the ‘Opti’ wave schematization method used to define 12 representative wave classes. Each rectangle is a wave class, small dots are all the wave records contained in the wave class and the large dot is the wave case used to represent the wave class (mean values of H_s and direction in the class). Highlighted wave classes are the output of the Opti routine. In this case, the twelve highlighted wave classes multiplied by a frequency occurrence (weight factor) defined by the method is used to represent the sediment transport patterns of all the 65 wave classes.

6.4.7. Methodology Used to Evaluate the Different Wave Climate Schematization Approaches

Results of each method of wave climate schematization are compared directly with the results from the model that utilized the reference wave climate (benchmark). The parameter selected for comparison is alongshore sediment transport.

The models were simulated without bed morphological changes but only potential sediment transport. This was done to eliminate cumulative /morphology history effects assuring that the outcome of the simulation of one wave case is not related with the previous case and consequently the sequencing of wave case does not influence the final result.

The sediment transport ($m^3/m/s$) related to each representative wave condition simulated was weighted according to the frequency of occurrence (seconds/year) of the wave condition to develop a transport map weighted per wave condition over the period of one year ($m^3/m/yr$). The resultant alongshore total transport was integrated along the grid lines perpendicular to the beach, resulting in values of net alongshore transport through each grid profiles (m^3/yr). The curves of net alongshore transport through grid profiles were derived in alongshore direction in order to quantify the gradients of transport in this direction. The gradients of transport are directly related to the patterns of erosion/sedimentation along the beach.

The results obtained using the representative wave conditions selected by the wave schematization methods were compared with the results of the reference simulation. RMSe (Root Mean Square Errors) were calculated to quantify the differences between the results obtained from the reference wave climate (65 wave cases) and the reduced wave climates.

RMSe were calculated as per equation 3 where N is the number of data points being compared, X represents the values related to the reference wave climate and Y represents the values related to the simulations conducted with a reduced set of wave conditions:

$$RMSe = \sqrt{\frac{\sum_{i=1}^n (Y-X)^2}{N}} \quad (3)$$

Relative RMS errors were not calculated directly in order to avoid having points with small magnitude of sediment transport/gradients affecting substantially the analysis of the results. Three groups of RMSe calculated from different model outputs of sediment transport and containing different unities, not directly comparable, were generated. The three groups of RMSe errors were normalized and used to calculate one error score for each simulation (table 3). The mean error (average of error scores) of each method was then calculated and used to rank the different methods.

6.5. RESULTS FROM SIMULATIONS WITH DIFFERENT WAVE CLIMATES

6.5.1. Reference Wave Climate

Net alongshore transport obtained with the simulation of 65 representative wave cases (reference wave climate) is shown in Figure 6. The transport magnitudes along the cross-shore grid lines were integrated to generate the curve of net alongshore transport Shown in Figure 6B. This curve was posteriorly derived in the alongshore direction to obtain the gradients of net alongshore transport (Figure 6.6C).

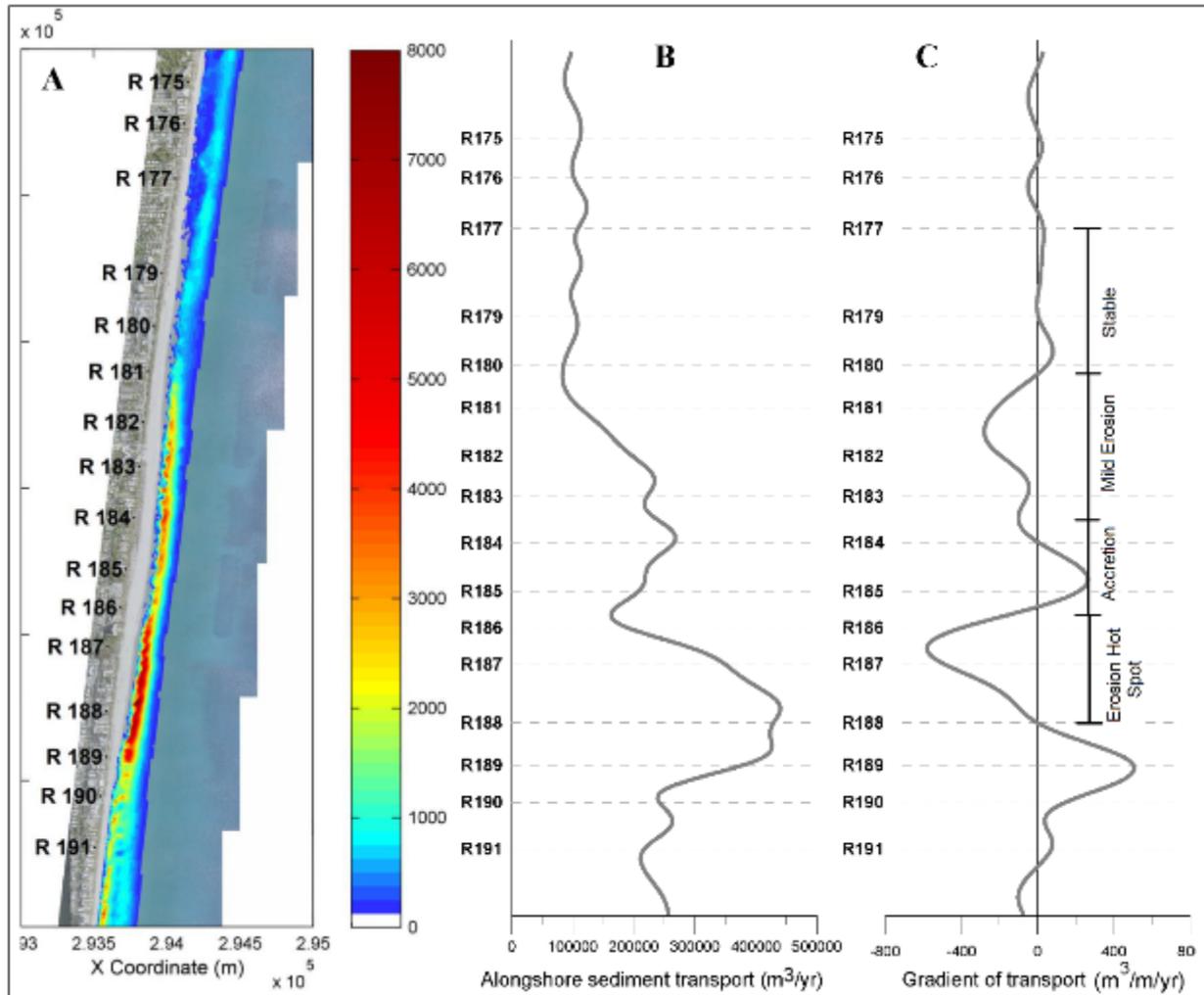


Figure 6.6. Results obtained using the robust wave climate with 65 representative wave conditions. A) Map of net alongshore transport; B) Net alongshore transport integrated along the cross-shore grid profiles and C) Gradients of resultant alongshore total transport, positive gradients indicate accretion while negative gradients indicate erosion

Positive values of transport indicate sediment transport from north to south. Effective sediment transport occurs within a narrow surf-zone (Figure 6.6A). An increase in alongshore sediment transport magnitude from north to south is observed in Figures 6.6A and 6.6B. The increase is resultant from borrow area effects (Benedet and List, 2008) and by the effect of the nourishment project (between monuments R180 and R188). The gradients of alongshore sediment transport are shown in Figure 6.6C, positive values indicate a decrease of transport (deposition) while negative values indicate an increase of sediment transport (erosion).

A review of several publications about Delray Beach behavior (Benedet et al., 2007, Hartog, 2006, Hartog et al., 2008, Benedet et al., 2006 and Benedet and List, 2008) indicates a stable beach between beach profiles R178 and R180 (updrift portion of beach fill project), an erosional area around beach profile R183 (mild erosional hot spot as per Benedet et al., 2007), an stable or slightly accretion area between beach profiles R184 and R185 and a highly erosional zone (erosion hot spot) located between beach profiles around profile R187. Figure 6C indicates that the model is reproducing well the beach behavior well documented in the literature.

6.5.2. Comparisons of Different Wave Schematization Methods with the Reference Wave Climate

The numerical results from the RMSE analysis are synthesized in Table 6.3. The score of the simulations in Table 6.3 corresponds to the sum of the normalized errors; these scores are also shown in Figure 6.7. For every method there is a general trend of increase on the magnitude of error as the number of representative wave conditions is reduced. The differences in performance between the different methods also increase as the number of wave cases is reduced (Table 6.3, Figure 6.7).

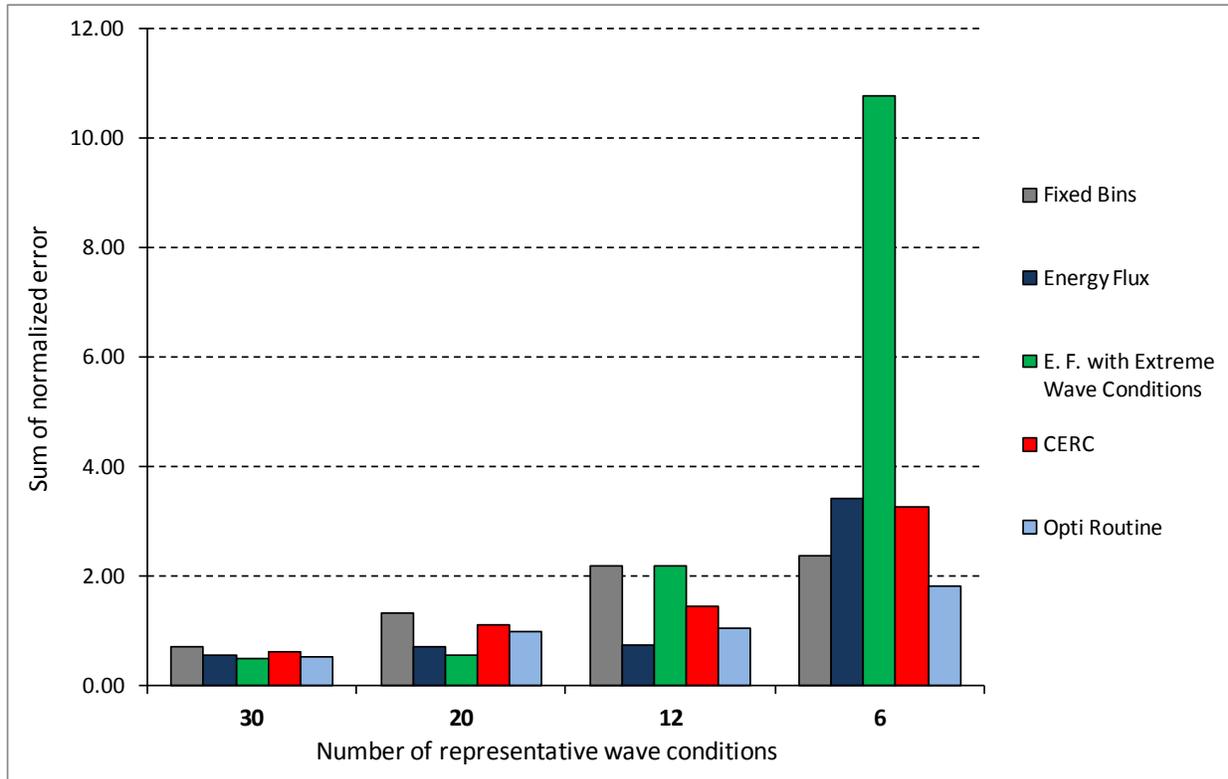


Figure 6.7: Normalized errors (in relation to Robust Model results) for the different number of representative wave conditions selected with the methods tested.

When the reference wave climate with 65 wave conditions is reduced to 30 wave conditions all methods show somewhat similar performance, independent of the methods of wave climate schematization/reduction used (Figure 6.7). When the wave climate is reduced to 20 wave conditions differences between the methods are already noticeable. For both wave climate with 30 wave conditions and 20 wave conditions the wave schematization method of the ‘Energy Flux with Extreme Wave Conditions’ exhibits the lowest sum of normalized errors, closely followed by the ‘Energy Flux Method’ and the ‘Opti Method’.

Table 6.3. Comparison of the methods of wave climate reduction.

METHOD	Number of wave conditions	Root Mean Square errors			Normalized errors			Score of the simulation	Average of the method
		Transport maps (m ³ /m/yr)	Alongshore transport (m ³ /yr)	Gradients of transport (m ³ /m/yr)	Transport maps (m ³ /m/yr)	Alongshore transport (m ³ /yr)	Gradients of transport (m ³ /m/yr)		
Fixed bins	30	16	2977	10	0.20	0.12	0.38	0.70	1.64
	20	25	7146	18	0.30	0.29	0.73	1.32	
	12	49	17249	23	0.60	0.70	0.89	2.19	
	6	70	8200	30	0.85	0.33	1.18	2.36	
Energy Flux	30	14	1729	8	0.17	0.07	0.32	0.56	1.36
	20	17	4714	8	0.21	0.19	0.30	0.70	
	12	17	5001	8	0.21	0.20	0.32	0.73	
	6	84	29906	30	1.02	1.21	1.19	3.42	
E. F. with Extreme Wave Conditions	30	11	2397	7	0.13	0.10	0.26	0.49	3.49
	20	15	2769	6	0.18	0.11	0.25	0.55	
	12	56	19921	17	0.69	0.81	0.68	2.17	
	6	311	93857	81	3.80	3.79	3.17	10.77	
CERC	30	13	3162	9	0.16	0.13	0.34	0.62	1.61
	20	24	7902	13	0.30	0.32	0.50	1.12	
	12	31	9766	17	0.38	0.39	0.69	1.46	
	6	74	27500	31	0.90	1.11	1.24	3.25	
Opti Routine	30	13	1840	7	0.16	0.07	0.28	0.51	1.09
	20	25	3480	14	0.30	0.14	0.54	0.99	
	12	32	3770	13	0.39	0.15	0.51	1.05	
	6	47	9446	22	0.57	0.38	0.87	1.82	
Standard deviation from zero		82	24742	25					

For every method there is a general trend of increase on the magnitude of error as the number of representative wave conditions is reduced. The differences in performance between the different methods also increase as the number of wave cases is reduced (Table 6.3, Figure 6.7).

When the reference wave climate is reduced to 12 and 6 wave conditions the differences between the different methods of wave climate schematization increases. With the reduced number of wave conditions (12 and 6 wave conditions) the method that better performs with a higher number of wave conditions, the ‘Energy Flux with Extreme Wave Conditions’ turns into the worst

performer (Figure 6.7). The ‘Energy Flux Method’ and the ‘Opti Method’ show best results when 12 wave conditions are used, (Figure 6.7). For the wave climate with 6 wave conditions the method that performs best is the ‘Opti Method’, followed by the ‘Energy Flux Method’. When 6 wave conditions are used, the ‘Energy Flux with Extreme Wave Conditions Method’ is again the worst performer (Figure 6.7).

6.6. APPLICATION OF THE BEST-FIT MODEL TO EVALUATE ENGINEERING INTERVENTIONS AT DELRAY BEACH

Beach volume change results from a one-year morphological change simulation for Delray Beach are shown in Figure 6.8. The simulation was conducted utilizing a wave climate consisting of 12 wave conditions, developed with the “Energy Flux Method”, and repeated in two cycles and with 3 hours spin-up time between successive wave conditions. The spin-up interval is necessary to reduce model instabilities due to abrupt changes in wave conditions that occur in the model but that do not necessarily occur so abruptly in nature.

The bathymetry used in the model was obtained a few months after the 1992 beach nourishment project at Delray Beach. The simulation indicates that there is a sand loss of 102,654 m³/yr within the beach nourishment area (R180-R188) in the first year after construction of the project. The simulated volume loss from the project area is in general agreement with the document volume losses from the project site for the same period from measured data. CPE (2004) using on measured beach profile data reported that between 2002 and 2004 the average volume loss from the Delray Beach nourishment project was 123,639 m³/yr. The immediate updrift area, between profile monuments R177 and R180 is gaining sediment at an approximate rate of 67,537 m³/yr while the immediate downdrift zone (between profile monuments R188 and R191) is losing sediment at an approximate rate of 47,413 m³/yr. These numbers and trends are consistent with the literature (Benedet et al., 2006, 2007, Hartog, 2006, CPE, 2004). Main reasons for this observed behavior were discussed in detail by Benedet *et al.* (2007), Hartog *et al.* (2008) and Benedet and List (2008).

Since the beach nourishment area is losing sediment at an average rate of 104,650 m³/yr, every 10 years a new beach nourishment project with approximately 1 million m³ of sediment must occur in order to maintain beach widths necessary for recreation and storm protection. The ~100,000 m³ of sediment lost each year is transported downdrift to Highland Beach, where beach widths are historically stable. In order to investigate possible ways to reduce volumetric losses at the Delray Beach nourishment project and reduce the volumetric needs of successive beach re-nourishment projects the morphological model was used to test a few hypothetical engineering interventions designed to reduce volumetric losses within the beach nourishment project limits. Interventions tested included removing all the offshore dredge pits by sediment re-filling, re-filling the deepest dredge pits identified as the main causes for the erosional hot spot at the south end of the nourishment project, adding a breakwater field consisting of three segmented breakwaters at the south end of the nourishment project and lastly adding a groin field consisting of three groins at the nourishment’s south end. The effects of each engineering solution on beach volume changes are summarized in Table 6.4.

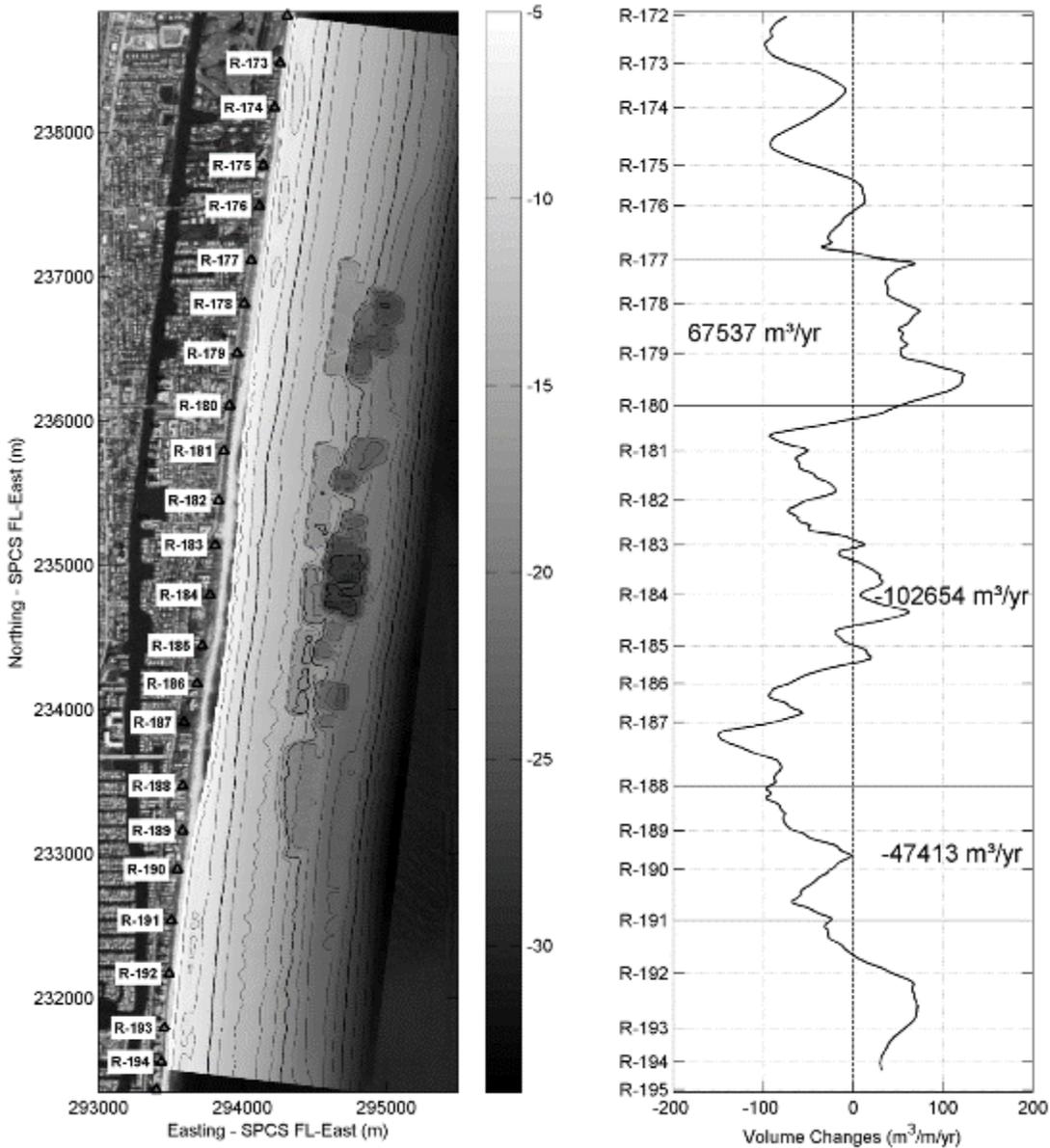


Figure 6.8. Beach configuration (left) and beach volume changes (right) resultant from one year morphologic simulation. Borrow areas can be visualized as holes in the left image.

When removing all dredge pits it was observed that volume losses from the fill area reduced from 102,654 m³/yr to 54,160 m³/yr, approximately 50% reduction (500,000 m³ of nourishment sand at every 10 years nourishment cycle). Updrift accretion trends were reduced from 67,537 m³/yr to 22,185 m³/yr (negative effect of 45,352 m³ updrift) while the erosion trend on the immediately downdrift segment was reduced by more than half (from 47,413 m³/yr to 20,407 m³/yr, positive effect of 27,000 m³). This trend suggests that the dredge pits have a positive (accretion) effect on the updrift area, a net erosional effect on the beach nourishment segment and on the proximal downdrift segment. Simulation of the model with all the dredge pits removed showed a more uniform distribution of erosion and deposition over the modeled domain (Figure 6.9) when compared to the current conditions (Figure 6.8).

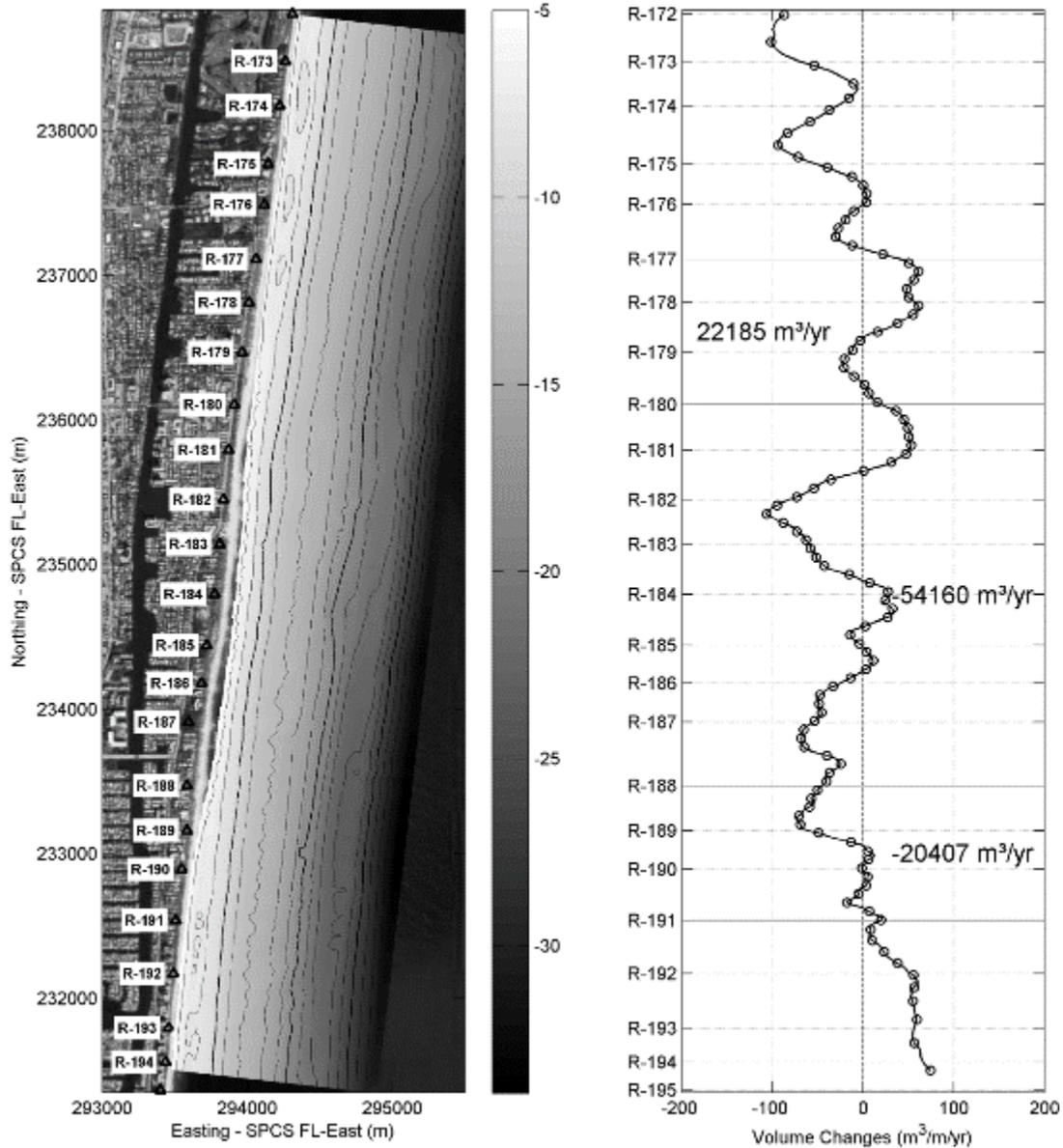


Figure 6.9. Bathymetric configuration representing the removal of all the borrow sites offshore from Delray Beach (left) and beach volume changes resulting from this bathymetric configuration based on a one year morphological simulation.

The volume changes of the scenario where the deepest borrow area is removed relative to the current scenario is shown in Figure 10. The volume change curve in Figure 10 was developed subtracting volume changes results from the 'no deep borrow area scenario' by the current scenario. Negative values indicate that the scenario caused additional erosion, positive values indicate that the scenario caused additional accretion and near-zero values indicating that the removal of the deep borrow area had no effect in the beach segment.

Table 6.4. Simulated volume changes at Delray Beach under different modeling scenarios representing coastal engineering interventions designed to reduce volume losses from the Delray Beach nourishment.

Scenario	Immediate Updrift (R177 to R180)	Nourishment Area (R180 to R188)	Immediate Downdrift (R188 to R191)
Current conditions	67,537	-102,654	-47,413
Removal of all dredge pits	22,185	-54,160	-20,407
Removal of deep dredge pit	63,861	-104,202	-38,246
Breakwater field at south end	68,188	-55,545	-76,082
Groin field at south end	66,373	36,263	-123,034

Removal of the deepest dredge pit (‘no deep dredge pit scenario’) situated between monuments R182 and R184 did not result in reduction of volume losses from the Delray Beach Project site but this intervention modifies the beach configuration within the nourishment project limits as it causes a total inversion in the location of erosional hot spots and depositional cold spots within the project site (Figure 6.10). The stable/accretion area between R184 and R185 becomes highly erosional and the erosional hot spot between R187 and R188 becomes stable to slightly accretion, however, the net effect within the project limits is near zero. Removing the deep dredge pit has a positive effect on the downdrift segment (net gain of 9,167 m³) indicating that this offshore feature is one of the main causes of the persistent erosion immediately downdrift of the beach nourishment limits.

Adding both the breakwater or groin field in the south end of the project had little to no effect in the updrift segment, significant positive effect within the fill limits and negative effects downdrift. The breakwater field reduced volumetric losses from the project limits by about 50% and increased downdrift erosion by about 60% (table 6.4, Figure 6.11). The groin field turned the entire beach nourishment project area into a mildly accretion area while increasing erosion of the beach segment immediately downdrift erosion by a factor of 3 (Table 6.4).

Relative or net volume changes for the breakwater simulation compared to the current conditions are shown in Figure 11. Breakwater effects are close to zero on the updrift zone, net positive by 47,108 m³/yr within the fill limits (470,000 m³ at every re-nourishment cycle) and net negative by -28,668 m³/yr downdrift. Results show similar trend but much stronger magnitude for the groin simulation with net positive effect within the beach fill segment of 138,900 m³/yr and net negative effect downdrift of -75,650 m³/yr (table 4).

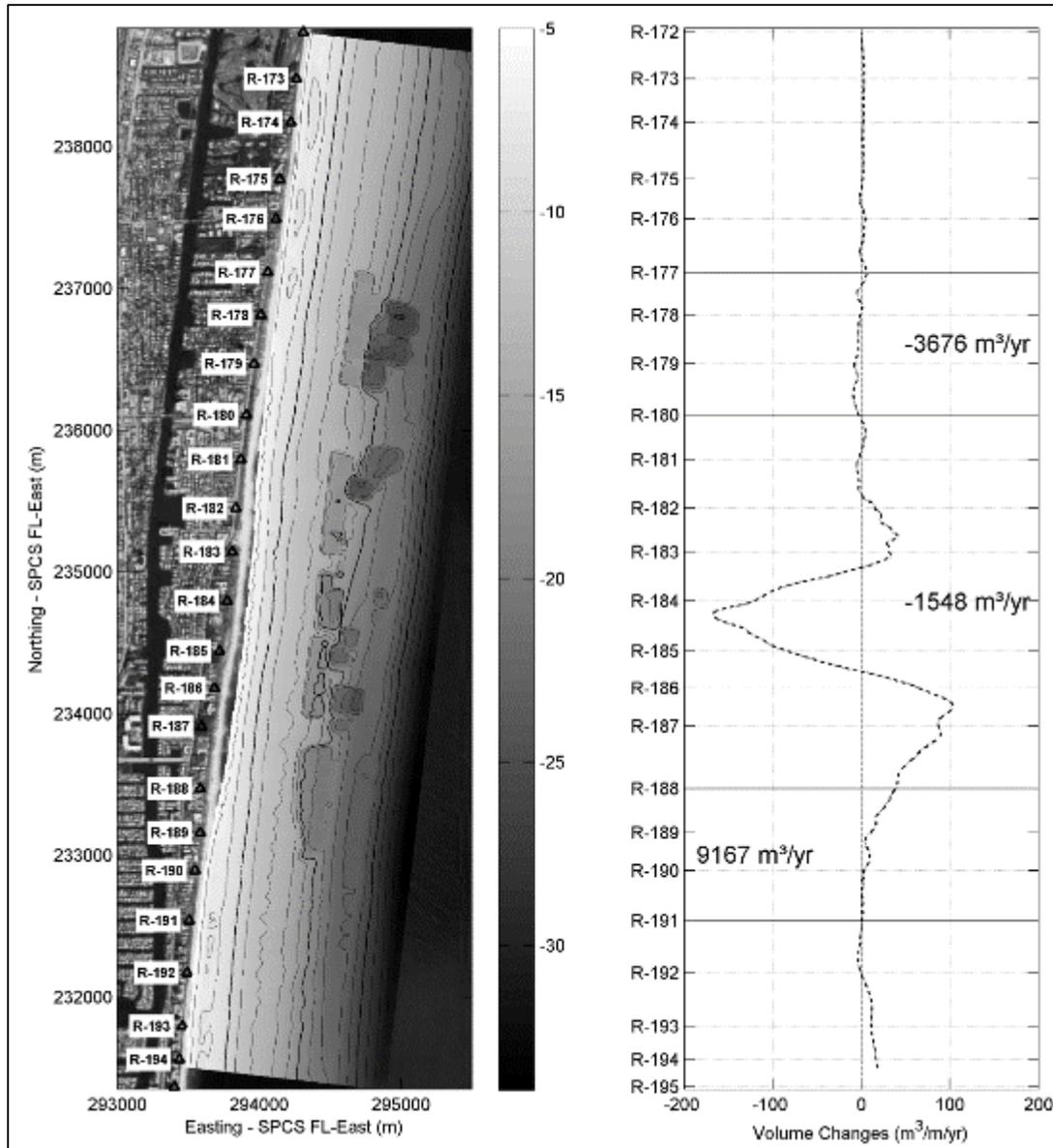


Figure 6.10. Bathymetric configuration representing the removal of the deepest borrow site between R182 and R184 (left panel) and relative or net beach volume change of this scenario relative to current conditions (right panel). Relative or net volume change was calculated by subtracting volume changes results from the no deep borrow area scenario by the current scenario and displays the relative effect of the removal of the deep borrow site.

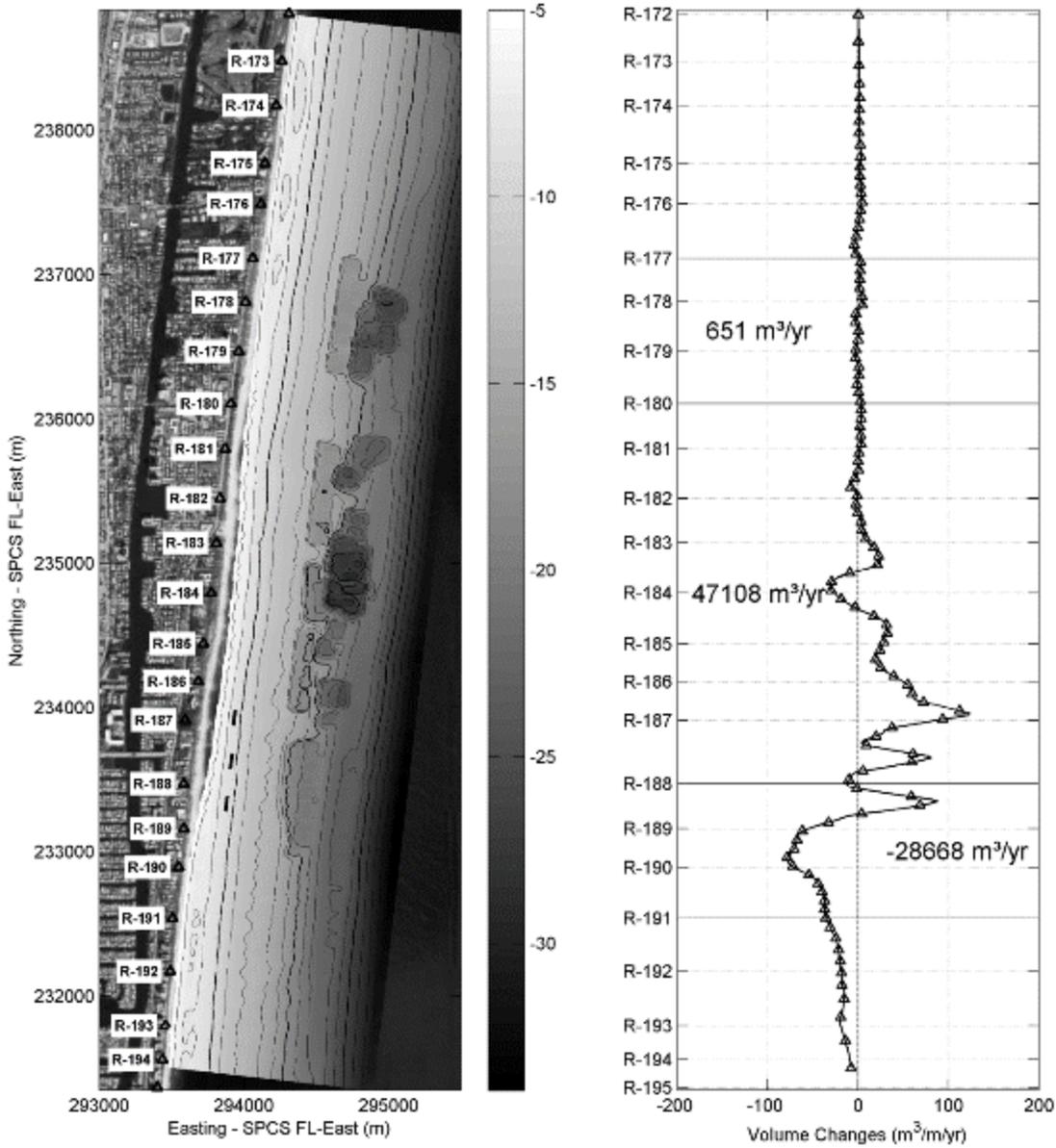


Figure 6.11. Bathymetric configuration with breakwater field between profile monuments R186.5 and R188.5 (left panel) and relative or net beach volume change of the breakwater scenario relative to current conditions (right panel). Relative or net volume change was calculated by subtracting volume changes results from the breakwater simulation by the current scenario and displays the relative effect of the removal of the breakwaters on beach volume changes.

6.7. DISCUSSION

6.7.1. Wave Climate Schematization

In this work, the authors reduced a full wave climate to a set of representative wave conditions to simulate sediment transport for a period of one year. When this is done, it is expected that the sediment transport resultant from the set of representative wave conditions will differ from sediment transport results obtained from simulations that utilize the full wave climate. However, depending of the method of wave climate schematization used, the number of representative wave cases selected, and the objective of the simulation, these deviations can be reduced to acceptable levels.

The ‘Opti Method’ and the ‘Energy Flux Method’ are the methods that consistently showed better performance in this analysis, regardless of the number of representative wave cases being used (Figure 6.7 and Table 3). Of these two the ‘Energy Flux Method’ with 12 wave cases was selected to be the method that offered the best performance based on the score of the simulation for this number of wave cases (Table 3). At 6 wave cases almost all methods performed relatively poorly, the Energy Flux Method performed better than all other methods with 12 wave cases and it was selected in this study for additional simulations of engineering interventions. The method offered the best effort-reward ratio (best performance at small number of wave cases), it is relatively easy to apply, and it is not subjective since waves are selected as a function of wave energy distribution. The Opti Method also reproduces extremely well the patterns of the model with the reference wave climate no matter the number of wave conditions used. The Opti-Routine is very efficient in mimicking the reference model results, however, it takes more effort and time to run when compared to the ‘Energy Flux Method’ because it requires preliminary runs of the sediment transport model with a very detailed wave climate, while the ‘Energy Flux Method’ is calculated directly from the wave records. Also the ‘Opti Method’ is designed to replicate the detailed wave climate with a random combination of waves. Many times wave cases considered important by model reviewers and governmental agencies are not included in the ‘Opti Method’ wave climate due to the random nature of wave climate selection. This is less likely to occur in the ‘Energy Flux Method’.

The other methods all contain certain limitations that justify its less optimal performance when the wave climate is reduced to a small subset of wave conditions (*i.e.* 12 or 6 wave cases). The performance of the ‘Fixed Bins Method’ gradually declined as the number of wave cases is reduced (Figure 6.7). The method can be scrutinized due to its subjectivity, since the user arbitrarily defines the height and the direction bins. The ‘Energy Flux with Extreme Waves Method’ is an attractive concept, however, because one wave case per direction bin is made of extreme waves this method requires a larger number of wave cases to perform well, as exemplified in Figure 6.7. The method can still be used if necessary to include extreme waves due to specific requirements in storm dominated coasts, however, when this method is used, a number of wave cases of at least 20 are recommended so that different wave conditions can be resolved and there is still room left to include a few extreme conditions in the wave climate. Alternatively, the user can include time series of extreme events in the middle of a schematized wave climate to simulate the extreme events in ‘real-time’ mode. Although the authors have used this approach in some storm-dominated coasts (*i.e.* barriers Islands in the Gulf of Mexico) this approach was not tested

in this study. The CERC method also produces good results but it does not perform as well as ‘Energy Flux’ and ‘Opti’ for a reduced set of wave conditions (Figure 6.7).

6.6.2. Effects of Sequencing of Wave Cases and Wave Case Transitions

In the previous section, in order to compare the different method of wave schematization the model was simulated without bed changes (morphological changes). When bed changes are activated the results, in terms of sediment transport, can be significantly different due to the feedbacks between morphology changes, waves, flows and sediment transport and to the ‘chronology effect’ (bed configuration resultant from previous wave condition affecting sediment transport and bed changes of the subsequent wave condition).

To reduce the ‘chronology effect’ the wave climate can be repeated in cycles. For example, in a 12 wave conditions climate there is a wave condition that represents three months out of the year. This condition can be broken down during the simulation in two or three pieces and alternated into the climate. The number of wave conditions to analyze remains the same (12), but the effect of the wave condition in the morphology is alternated with other wave conditions, similar to the natural environment. In the morphological model simulations demonstrated in the section where engineering solutions were evaluated the Energy Flux Wave climate, with 12 representative wave conditions, was repeated twice (two cycles) during a one-year morphological model simulation. The optimal number of cycles will depend on the judgment of the modeler and the characteristics of the wave climate in each region being modeled.

When a schematized wave climate is simulated, abrupt changes in wave conditions occur in the model that does not necessarily occur so abruptly in nature. For example, if a wave condition with 1.0m Hs, 8s Tp, and 141° direction is directly followed by a wave condition with 3.5m Hs, 10s Tp, and 51° direction, a series of model instabilities that will cause abrupt variations in sediment transport will result. If morphology change is allowed to take place during this transition, strange and unrealistic patterns of morphological change can occur, therefore it is recommended to add a spin-up interval every time that there is a transition from one wave condition to the other (Walstra *et al.*, 2013). The amount of spin-up time required will depend on how different the wave conditions transitioned are, sensitivity tests are recommended to determine optimum intervals. In our model spin-up intervals of 3 hours (simulation time) between subsequent wave conditions were used since this was the period that took for the sediment transport magnitude to equilibrate and stabilize with the new wave condition at different water depths.

6.6.3. Interventions to Reduce Volumetric Losses from the Delray Beach Nourishment Project

Numerical model simulations of engineering interventions aimed at reducing volumetric losses from the Delray Beach nourishment project demonstrated that, no matter what intervention is proposed, the end result affects the overall sediment budget of the area with varying effects at the updrift and downdrift segments of the beach nourishment project. If volumetric losses from the beach fill are reduced the downdrift beach segments will likely ‘miss’ the sediment supply previously received but now cutoff. What the coastal engineering interventions intend to achieve is a ‘balancing act’ between sand retention and adverse impacts.

Results of the model simulations performed here demonstrate that removal of all the borrow areas by sediment re-filling or fine-tuned structures at the beach nourishment downdrift (south) end can achieve this balancing act efficiently and reduce project losses by half with varying effects downdrift. The best solution in terms of tradeoff between beach fill volume loss and downdrift impacts appears to be the backfilling of dredge pits. This alternative produces less accretion updrift, reduces fill volume losses by nearly half and produces a positive effect on the immediate downdrift coastline, however, it is highly likely that beaches located further downdrift, outside of the model domain, will feel the impact of the sand supply being retained within the beach nourishment project limits and proximal beach segments. The next best alternative is the introduction of a permeable structure at the southern end of the beach fill, represented here by the three segmented breakwaters (Table 6.3). This solution also reduces the fill volume loss by half, has no effect on updrift shoreline, but it causes an increase in the erosion of the beach immediately downdrift (Table 6.3). Re-nourishment requirements at Delray Beach would go to zero and the beach fill would become slightly accretion with the groin field solution, however, the magnitude of downdrift erosional impacts is the largest of all alternatives tested (threefold increase).

Breakwater effects were milder compared to the effects from the groin because it allows sediment bypassing during high energy conditions. Groin effects were more pronounced compared to the breakwater because the groins were impermeable extended across the entire surf zone and trapped almost all of the sediment transported from north to south in this beach segment, consequently leading to strong erosion impacts downdrift.

6.8. CONCLUSIONS

Five methods of wave climate schematization designed to reduce a full wave time-series into a representative set of conditions for coastal morphological modeling were evaluated in this work. The techniques were named: (1) 'Fixed Bins'; (2) 'Energy Flux'; (3) 'Energy Flux with extreme Wave Condition'; (4) 'CERC'; and (5) 'Opti'. Model sediment transport results from each method were compared against results from a simulation with a very detailed wave climate. Of all the methods of wave climate schematization tested the Energy Flux Method and Opti Method showed best results in terms of representing accurately the sediment transport of the very detailed wave climate with a reduced set of wave conditions.

The Energy Flux Method was identified as the preferred technique by the authors because it is relatively easy to apply, it is not subjective since waves are selected as a function of wave energy distribution and shows satisfactory performance even when compared to more complex and time intensive methodologies such as the Opti method. The Opti method performs better than all the other methods when a very small number of wave cases are used to represent an annual wave climate (*i.e.* 6 wave cases). Conversely, the Energy Flux Method with Extreme Wave Conditions performs well only when a larger number of wave cases is utilized to represent an annual wave climate. The Fixed Bins method in general did not produce comparative good results and it contains the bias of subjectivity. The CERC Method also shows acceptable results but its performance is slightly inferior when compared to the Energy Flux or Opti methods.

The test conducted also indicate that a number around 12 representative wave cases is enough to represent an annual wave climate compared to a detailed wave climate. This number of wave cases can make annual morphological simulations fast and facilitate critical analysis of model

results since there are only 12 wave cases to enquire when tasked to evaluate the effects of each wave condition in the overall model results.

The methods of wave climate schematization described here can be used for morphological modeling in most wave-dominated coasts around the world. The authors, for example, have extensively used the energy flux (EF) method in many numerical modeling efforts in applied coastal engineering studies on the east coast of the USA and Brazil. However, like any methodology, there are limitations and it is not the most adequate solution for all cases. The authors recognize, for example, that in coastal segments with very mild wave climate where morphology changes are dominated by episodic major storms (i.e. the coasts of Texas and Louisiana in the Gulf of Mexico), the EF method is not the most-suitable method. In these coasts, we recommend using a hybrid approach, where long calm periods can be represented by a set of wave conditions (obtained using the EF method) but are intercalated by Hurricane and Tropical storm hourly time-series. When such hybrid approach is adopted, new challenges surface such as: which storms to choose, when the storms should hit in the wave climate in a long-term (i.e. 10 yr or 20 yr) morphological simulation etc. To address this challenges a probabilistic approach, when many simulations with different storm ensembles are conducted, may be more appropriate. Additionally, in areas where tides dominate the method of wave climate schematization selected becomes less relevant and in some areas that are extremely shallow, windy and fetch-limited wind climate schematization becomes equally important as wave climate schematization.

The optimized morphological model, with an annual wave climate consisting of 12 representative wave cases defined utilizing the Energy Flux Method, was applied to test coastal engineering interventions aimed at reducing volume losses from the Delray Beach nourishment project. A breakwater field or removal of all dredge pits produced results that indicated a reduction in beach volume losses within the project limits by almost half with minimal effects immediately downdrift. The groin field halted erosion completely within the project site but increased downdrift erosion threefold. Removal of the deep Dredge pit identified as the main cause for the erosional hotspot in previous by Benedet and List (2008) caused an abrupt modification in the location of erosion hot spots and accretion cold spots within the project limits but had no net effect in volume losses within the beach nourishment limits.

If volumetric losses from a beach fill project are reduced by engineering interventions erosional downdrift impacts are expected as sediment supply previously received by downdrift beaches is now cutoff by the sand retention measure. This study demonstrates that some engineering solutions such as the backfilling of all the dredge pits or introduction of permeable structures at the downdrift (south) end of the Delray Beach Beach nourishment project can improve the performance of the nourishment reducing volumetric losses with mild downdrift effects. Since the downdrift beaches are receiving about 100,000 m³/yr of sediment lost from the nourishment project, a reduction of these losses in half implies that the downdrift beaches will still be receiving 50,000 m³/yr.

Retaining some of the sand within the Delray Beach nourishment project limits makes perfect sense from an engineering point of view, but each intervention evaluated here affects the updrift and downdrift shorelines in a different way. There is also a cost associated with the construction of the intervention, which may or may not be offset by the savings caused by the reduction of volume losses from within the beach nourishment limits. In summary, reduction of volume losses from the Delray Beach Nourishment Project can be achieved by targeted engineering interventions,

however, the economic and environmental feasibility of these interventions need to be further evaluated in detailed feasibility study prior to implementation.

CHAPTER 7. CONCLUSION AND RECCOMENDATIONS

7.1. SUMMARY CONCLUSIONS

This study was conducted in order to understand the processes that control the performance, in terms of volume losses, of the Delray Beach nourishment program. Of particular interest was the understanding of the driving forces behind the development of persistent erosional hot spots within the geographical boundaries of the Delray Beach nourishment project. Analyses of measured data as well as numerical modeling of waves, currents, sediment transport and morphology were the main methods used to achieve this objective. The main objective of the study was achieved. We have a much better understanding of the behavior of the Delray Beach nourishment project and what physical processes cause the accelerated hot spot erosion observed year after year at the south end of the project. Along the journey to understand the processes controlling nourishment performance at Delray Beach there were other important findings and methodologies developed that are relevant to morphological modeling and design of beach fills and dredge pit excavation projects. Detailed summary conclusions focusing on the four main research objectives are provided below.

7.1.1. Evaluate the performance of the Delray Beach nourishment project with focus on identification of erosion hot spots and accretion cold spots.

Alongshore variability on the morphodynamic response of the Delray Beach nourishment project was evaluated in Chapter 2. Potential hypothesis to explain the erosional hot spot occurrence in the downdrift end of the beach nourishment were presented and preliminarily evaluated. The evaluation was based on literature review, analysis of 8.5 years of data post-construction of the 1992 beach renourishment project and preliminary numerical modeling.

It was observed that most of the volume loss occurred in the first two years after the nourishment as the fill adjusted in planform and that there was large annual variability in fill erosion rates as a function of inter-annual variation in wave climate associated with tropical and extra-tropical storm activity. Two zones with higher erosion were identified and classified as erosion hot spots (EHS) and one zone in the middle of the nourishment project was classified as a stable, or an accretion cold spot. Volume losses at one EHS occurring in the south end of the project (between R186 and R188) were at least 100% greater than the average volume loss of the nourished area. About 50% of the total volume loss from within the nourishment limits accrued from this from 600 m long EHS, in a project that is 2.7 km long. This behavior persists to this date and was not exclusive from the time period evaluated in chapter 2, as demonstrated in the introductory chapter of this thesis.

Hypothesis raised in chapter 2 to explain the EHS erosion included the influence of nearshore bathymetric features (barrier coral reefs, reef gaps and borrow pits) on nearshore wave propagation, and change in shoreline orientation in the south end of the project due to the beach nourishment project. These hypotheses formed the basis for the work conducted in the following chapters of this thesis.

7.1.2. Understand the physical processes driving project performance at Delray Beach and causing the formation of erosion hot spots.

Three main hypotheses to explain the erosion hot spots were investigated: (1) Effects of nearshore bathymetric features on wave propagation and coastal processes; (2) Effects of shoreline orientation induced by the fill protuberance; (3) Effects of differential alongshore grain size distribution.

Data analysis conducted in chapter 2 provided enough evidence to conclude that grain size differences alongshore were not the cause of increased erosion of EHS segments since grain sizes are not persistently finer where higher erosion is observed or vice-versa. Variations in grain size distribution within the project area can be considered to be minor so grain size different cannot explain hot spot development.

The data and numerical modeling evidence analyzed in chapter 3 indicated that gaps in the offshore barrier reef system did not the cause the EHS. This conclusion was based on the fact that the effects of the barrier reefs on the nearshore waves and currents were relatively minor as evidenced by numerical model simulations. Alongshore variability in wave height and associated pronounced areas wave shadowing and focusing zones observed along the project area were attributed to wave transformation over the dredge pits.

In Chapter 2 it was observed that near the EHS segment on the south end of the project (between R186 and R188), variations in nearshore wave heights were relatively small compared to other segments of the project. Even though gradients in wave heights were relatively small at the EHS segment in the south end of the project, current modeling in Chapter 2 and 3 demonstrated clearly that alongshore currents are stronger in this EHS segment where the highest volumetric losses are observed. Because the gradients in wave height in this areas were smaller when compared to other project segments it was concluded at the time (Chapters 2 and 3) that the localized increase in current velocity and sediment transport in the south end of the project was likely caused by changes in shoreline orientation induced by the beach nourishment.

The change in shoreline orientation at the south end of the fill is more pronounced during the first two years post construction where fill alongshore adjustment is taking place and there is a large seaward protuberance introduced by the fill. However, the persistency of high erosion rates at the same beach segment during the entire beach nourishment lifetime suggested that other processes were at play, possibly alongshore gradients in hydrodynamics induced by offshore borrow areas. This observation posed an important question: if the wave height gradients at this EHS beach segment were not as pronounced as in other project segments, why this zone behave so differently than the other project segments throughout the entire nourishment lifetime? Since reef gaps and grain size distribution were ruled out there were two other possible causes left to be investigated: shoreline orientation changes and dredge pit effects, however, the relative effects of these morphological features (shoreline angle and borrow areas) on the increased current velocities observed on the Erosional Hot Spot Segment could not be differentiated in Chapters 2 and 3.

In Chapter 2 evidence suggested the EHS was likely due changes in shoreline orientation, in Chapter 3, when some additional sediment transport and morphological modeling was conducted it was possible to identify prominent effects from the dredge pit on sediment transport and morphology change on the EHS beach segment. However, as stated in chapter 3, “although the hydrodynamic analysis suggested that the shoreline orientation at the south end of the fill area may cause the erosion hot spot in that location, morphological simulations were inconclusive in this matter and a separation between Dredge pit and shoreline orientation effects was not evident in the results from the current morphological runs”.

In Chapter 4 the relative effects of shoreline orientation and dredge pits on the erosional hot spot were further investigated by integrated simulations of waves, flows, sediment transport and beach morphology changes, together with a detailed analysis of forcing in the flow momentum equation to investigate processes behind current accelerations in the south end of the beach fill.

Physical processes causing the observed behavior were investigated using a simplified schematic model that was created inspired in the Delray Beach case with shore parallel contours, a deep dredge pit in the middle of the model domain and oblique waves replicated NE swells in the study area. Using the schematic model it was demonstrated that the beach changes behind a deep dredge pit were due to the interaction of wave forces (roller force), differentials in wave setup (pressure gradient term), and variable bed shear stress. These processes cause a unique pattern of flow and sediment transport distribution behind the bathymetric anomaly introduced by dredging. Decrease in current velocity and sediment transport occurred towards the wave shadow zone, causing deposition of sediments and beach accretion. The lowest currents were observed in the downdrift end of the wave shadow zone and in the beginning of the wave focusing zone located immediately downdrift of the shadow zone. Lower currents were observed even in the beginning of the wave focusing zone because pressure gradients forces currents in an opposite direction as the wave induced flow. Current acceleration and erosion hot spot development downdrift of the accretion zone is due to flow accelerations as the gradients in wave setup (pressure gradient term) becomes insignificant, shear stress is still low, and the wave forces gradually increase to normal levels. Under these circumstances the flow velocities gradually increase until it reaches equilibrium with local bed shear stress. This leads to a gradual increase in sediment transport capacity (upward sloping sediment transport curve) and conditions favorable to EHS development (little sediment coming in and large sediment load going out). This process persists until current velocity and sediment transport is stabilized by the increase in bed shear stress.

Because of this complex interaction between roller force, wave setup gradient, and bed shear stress, under oblique waves the zone of current acceleration does not necessarily coincide with the area of wave focusing. In fact it was demonstrated in chapter 4 that in the area of wave focusing the pressure gradient forces are opposite to the wave induced roller force, currents and sediment transport accelerate just downdrift of the wave focusing zone, where the erosional hot spot occurs. This explains why in the EHS segment there are stronger currents and sediment transport potential than anywhere else in the project site, but this area does not coincides with the largest alongshore gradients in wave height, but it is located just downdrift of it.

By applying the lessons learnt from the schematic model to the Delray Beach model and investigating simulations with several different bathymetric configurations (selectively removing dredge pits by interpolation) it was concluded that a dredge pit with a 12 m maximum depth of cut, located in the center of the Delray Beach project area about 1 km offshore, was the main cause

for the EHS in the south end of the project, which is located between 1 km and 1.5 km downdrift of the borrow site. The hot spot is responsible for about 50% of the erosion from the project site, removing the dredge pit by backfilling reduces the hot spot erosion drastically, but also increases erosion in areas where there is beach accretion or stability (the dredge pit is also responsible for beach stability in the center of the project between profile monuments R184 and R185).

7.1.3. Study beach response to offshore dredge pits and dredge pit design parameters using a natural laboratory (Delray Beach) and hypothetical model tests inspired on the Delray Beach case.

Delray Beach has ten dredge pits located directly offshore from the project site. These pits were dredged initially in 1973 and the latest dredging event occurred in 2013. The dredge pits dredged over the years exhibit different shapes and cut depths. The oldest dredge pits (1970s, 1980s) are more circular and very deep (up to 10 m depth of cut), the most recent pits were shore parallel (rectangular shaped), and had shallower depths of cut (generally 1m to 3m). These different cut depths and shapes reflect the changes in equipment, dredge supervision and environmental permitting requirements over the years.

Over the course of this work it was noted that the deeper and steeper borrow pits (dredged in 1973 and 1978) have the larger influence on the waves (causing the large fluctuations in significant wave height), while the shallower (about 2 m cut below the seabed) and less steep Dredge pits (dredged for nourishments since 1984) show negligible influence on nearshore waves (fluctuations in wave height are less than 5%), suggesting that nearshore dredging is possible without significantly affecting the wave regime. Based on this observation it was decided to dedicate Chapter 5 of this thesis to study the effects of the different dredge pit design parameters (shape, cross-shore and alongshore length, depth of cut, distance from shore, water depth in which dredging occurs) on incoming waves and adjacent beach volume changes. The study was conducted using the schematic model developed in chapter 4 and focused on defining guidelines to reduce the unwanted effects from dredging interventions on the adjacent coasts.

Results shown in chapter 5 indicate that, maintaining similar dredge volumes, dredge pit designers can reduce by as much as half the unwanted impacts on adjacent shores by tuning dredge pit design parameters, such as cut depth, the cross-shore width of the pit, and, if the sand reserve is large enough, by increasing the distance from the shore and the water depth. A dredge pit that has a long, shore-parallel extent and a narrow, cross-shore extent, with a shallower depth of cut, produces fewer nearshore impacts than a dredge pit that has a wide, cross-shore extent with a deeper depth of cut. Designers should favor shore-parallel, shallow, long, and narrow pits whenever possible in lieu of deeper cuts with wider cross-shore extent.

The regional bed slope, water depth, and distance from shore are also important parameters that influence the magnitude of the dredge pit impacts on adjacent shores. In general, pits in deeper water produce fewer effects, and greater water depths should be sought when economically and technically feasible. Distance from shore affects not only the magnitude of the impacts but also the location of the impacts, especially in areas with oblique wave dominance. Effects from pits located 6 km offshore can be found up to 4 km downdrift of the pit under oblique waves. This suggests that impacts can be “targeted” to occur in less-sensitive beach segments in certain specific cases.

Dredge pit effects not only cause erosion but can also cause beach accretion. Manipulation of incoming waves to create beach accretion may be unintentional, as is the case for most dredge pits, but it can also be created intentionally for shore-protection purposes in small, localized areas, similar to what is done using artificial reefs. Note, however, that, adjacent to the accretion zone, there will always be erosion zones because of the increase in sediment transport potential from the accretion zone (the area protected from waves) to the wave-exposed zone. If dredging projects are built with this purpose (create beach accretion zones) it must be evaluated if the erosion forecasted adjacent to the accretion zone can be tolerated without negative effects.

Useful guidance was provided in chapter 5, with such insights and assistance of site-specific models possible adjustments to the design of dredge pits can be made, to develop optimized pit designs in order to reduce impacts on adjacent beaches. It must also be considered that optimum pit design may also be constrained by other issues, such as sediment availability, feasibility of extraction, cost of extraction, as well as environmental restrictions.

7.1.4. Evaluate engineering interventions designed to reduce volumetric losses from the project site and improve overall project performance.

In chapters 3 and 4, annual morphology simulations were conducted utilizing bathymetric scenarios where the deep dredge pits, as well as all the dredge pits were removed. In these simulations it was noticed that backfilling only the deepest dredge pit dredged in 1973 can reduce the hot spot erosion drastically but also increases erosion in areas there is beach accretion or stability (the deep dredge pit is also responsible for beach stability in the center of the project between profile monuments R184 and R185). Removing all the dredge pits from the model domain by backfilling, resulted in less erosion from within the beach nourishment limits (net effects are positive) and caused a relatively a more uniform response of the beach fill alongshore. However, as noted in Chapter 3, the annual morphological simulations showed sensitivity to sequencing of the annual wave climate, that is, different sequences of waves in the annual wave climate lead to very different model results in terms of annual beach volume changes. Also calibration of volume changes modeled versus observed could be improved. Both observations suggest that there is room for improvement in the annual wave climate used in the morphological simulations.

In Chapter 6 the research work focused on two main tasks, one was to reduce the morphology model results sensitivity to the sequencing of wave climate and to make sure that the annual wave climate being used was at the same time computationally efficient and represented well the erosional hot spot at the south end of the project. The second task was to evaluate the effects of dredge pit backfilling and coastal structures on magnitude of hot spot erosion and impacts to the beaches located immediately downdrift of the fill.

Five methods of wave climate schematization designed to reduce a full wave time-series into a representative set of conditions for coastal morphological modeling were evaluated in Chapter 6 to achieve the first task. The techniques were named: (1) 'Fixed Bins'; (2) 'Energy Flux'; (3) 'Energy Flux with extreme Wave Condition'; (4) 'CERC'; and (5) 'Opti'. Model sediment transport results from each method were compared against results from a simulation with a very detailed wave climate, the benchmark wave climate. Of all the methods of wave climate schematization tested the Energy Flux Method and Opti Method showed best results in terms of representing accurately the sediment transport of the benchmark wave climate with a reduced set of wave conditions.

The Energy Flux Method was identified as the preferred technique because it was relatively easy to apply, it is not subjective since waves are selected as a function of wave energy distribution and shows satisfactory performance even when compared to more complex and time intensive methodologies such as the Opti method. The Opti method performed better than all the other methods when a very small number of wave cases are used to represent an annual wave climate (*i.e.* 6 wave cases). Conversely, the Energy Flux Method with Extreme Wave Conditions performs well only when a larger number of wave cases is utilized to represent an annual wave climate. The Fixed Bins method in general did not produce comparative good results and it contains the bias of subjectivity. The CERC Method also shows acceptable results but its performance is slightly inferior when compared to the Energy Flux or Opti methods.

The test conducted also indicate that a number around 12 representative wave cases is enough to represent an annual wave climate compared to a detailed wave climate. This number of wave cases can make annual morphological simulations fast and facilitate critical analysis of model results since there are only 12 wave cases to enquire when the modeler is tasked to evaluate the effects of each wave condition in the overall model results. For comparison purposes, annual morphology simulations conducted in Chapters 3 and 4 utilized the fixed bind method with 6 wave cases).

The optimized morphological model, with an annual wave climate consisting of 12 representative wave cases defined utilizing the Energy Flux Method, was applied to evaluate coastal engineering interventions aimed at reducing volume losses from the Delray Beach nourishment project by addressing the hot spot erosion.

A breakwater field or removal of all dredge pits produced results that indicated a reduction in beach volume losses within the project limits by almost half with tolerable effects immediately downdrift. The groin field halted erosion completely within the project site but increased downdrift erosion threefold. Removal of the deep dredge pit identified as the main cause for the erosional hotspot in previous work conducted by Benedet and List (2008) caused an abrupt modification in the location of erosion hot spots and accretion cold spots within the project limits but had no net effect in net volume losses within the beach nourishment limits, confirming the findings reported in Chapter 4.

The work conducted in chapter 6 demonstrates that engineering solutions such as the backfilling of all the dredge pits or introduction of permeable structures at the downdrift (south) end of the Delray Beach nourishment project can improve the performance of the nourishment reducing volumetric losses with mild downdrift effects. Since the downdrift beaches are receiving sediment lost from the nourishment project “free of costs”, a 50 percent reduction of these losses implies that the downdrift beaches will still be receiving sediments from the Delray Beach nourishment project, but at a smaller magnitude.

Retaining more sand within the Delray Beach nourishment project limits makes good sense from an engineering point of view, but each intervention evaluated in Chapter 6 affected the updrift and downdrift shorelines in different ways. There is also a cost associated with the construction of each intervention, which may or may not be offset by the savings caused by the reduction of volume losses from within the beach nourishment limits. In summary, reduction of volume losses from the Delray Beach Nourishment Project can be achieved by a series of targeted engineering

interventions. However, the economic and environmental feasibility of these different interventions need to be further evaluated in detailed feasibility study prior to implementation.

7.2 RECOMMENDATIONS

Based on the findings of this research work the following recommendations are provided. The recommendations provided here fall in two categories: Generic recommendations that can be applied to the design process of beach nourishment projects and site-specific recommendations for the Delray Beach nourishment program.

- Erosion Hot Spot Countermeasures: Erosional hot spots are a recurrent problem in many beach fills across the USA. Many hot spots are due to inlet effects when the beach fill is located in areas close to non-stabilized inlets and subject to fluctuations in channel direction. Open ocean beach fills that are not influenced by migrating inlet channels develop erosional hot spots due to the beach response to bathymetric anomalies offshore (*i.e.* Delray Beach), or structural controls (bedrock) that cause structurally controlled abrupt changes in shoreline orientation. Instead of continuing to fight the erosional hot spots by placing more sand in the system (what may cause the losses to be even greater), it is recommended to use the full suite of field measuring techniques and numerical models available to us nowadays to enable the identification of the causes of erosional hotspots so then intelligent engineering solutions can be designed to address the problem.
- Wave Climates for Morphological Modeling: The development of schematized annual wave climates for coastal morphology modeling should be carefully investigated and tested before the morphology model can be used as an engineering tool. What worked in the study area (*i.e.* Opti and Wave energy Flux methodologies with 12 wave cases), is likely to work in other wave dominated coasts with similar wave climates and tidal amplitude around the world but may not be ideal in some other areas. In the Louisiana Coast (USA), for example, probabilistic tropical storm modeling, or the use of wave case scenarios where time-series of tropical storms simulated in 'brute force' are intercalated with averaged wave cases may be more appropriate. Each case has its specific requirements and the modeler must respect the peculiarities of each coast. There is no "one formula fits all" when dealing with annual wave climate schematization for morphological modeling of wave dominated coasts.
- Dredge Pit Design: Although impacts of dredge pits on adjacent beaches is a hot topic when permitting dredging works in the USA these days, little attention has been given in the past to dredge pit design. The work conducted here shows that designs can be optimized to significantly reduce adverse impact from offshore dredging on adjacent beaches. As a suggestion for further work the author recommends further study of dredge pit design parameters utilizing physical and numerical models under different wave and tide climates to develop design guidelines for other coasts around the world.
- Dredge Pit Excavation for Coastal Protection: It was demonstrated in this thesis that selective dredging can achieve similar effects as offshore structures in terms of beach accretion and erosion. Wave manipulation by dredging to create beach accretion can be intentionally performed for shore-protection purposes in small, localized areas, in way similar to what is done using artificial submerged reefs. This alternative approach should

be considered in combination with the other alternatives coastal engineers have to solve beach erosion problems.

- Prediction of Accretion Salient Behind Bathymetric Anomalies: There are many empirical relationships to predict salient growth as a function of placement of offshore structures (*i.e.* breakwaters) and the work performed here demonstrates that selective dredging can achieve similar effects in terms of salient growth. However, when there is salient growth, there will always be associated erosion zones due to the increases in sediment transport potential from the accretion zone to adjacent wave-exposed zones. The same processes that cause the salient to grow in the first place will also cause downdrift erosion. Empirical relationships commonly used to estimate shoreline response to offshore structures such as breakwaters and submerged reefs, in this regard, provide an incomplete answer, since they address only the estimates of benefits (*i.e.* salient growth), disregarding adjacent erosion zones that occur associated with beach salient growth. Recent advances of morphological modeling allows coastal engineers to reasonably estimate the magnitude and geographical locations of beach erosion and deposition zones which may result from nearshore dredging projects, or placement of offshore structures. With such estimates a sensitivity analysis of possible adjustments to the design of these features (dredge pits and coastal structures) can be made, in order to develop optimized designs that reduce downdrift impacts to manageable levels. In summary, analytical formulations are a good first order approximation of the effect of offshore features on the adjacent coast, but more detailed investigation with morphological models, used as a design tool, should be conducted prior construction of such interventions.
- Improvements to the Delray Beach Nourishment Program: Lastly, pertaining to the Delray Beach nourishment project: This study demonstrated that engineering solutions such as the backfilling of all the dredge pits or introduction of permeable structures at the downdrift (south) end of the Delray Beach nourishment project can improve the performance of the nourishment reducing volumetric losses by about half with mild downdrift effects. Downdrift beaches are receiving the sand lost from the beach nourishment project, if these losses are reduced the city of Delray Beach will save money, but downdrift municipalities will receive less sand. It must be considered, however, that even with a reduction of losses from the Delray Beach Nourishment Project, downdrift communities will still continue to receive some sediments lost from the nourished area and thus, be on the positive side. The real questions to be asked for management purposes are: is the City of Delray Beach interested in such reduction or it prefers to continue to overfill this area every renourishment cycle to account for the additional losses from the hot spot? Will there be sand available to sustain volumetric requirements of the nourishment program for the next 50, 100 or 200 years? Can the engineering interventions proposed (dredge pit backfilling or permeable structures) be permitted by the state environmental agencies? An economic and environmental feasibility study of these interventions is recommended prior to implementation of any of the solutions investigated in this work.

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APPENDIX A. DELRAY BEACH - HISTORICAL PHOTOS



Delray Beach, 1950s.



Delray Beach, 1960s.



Delray Beach experiences erosion problems in the late 1960s.



In response to erosion problems and rocks were thrown in the base of the eroded dune with no design criteria, late 1960s to early 1970s.



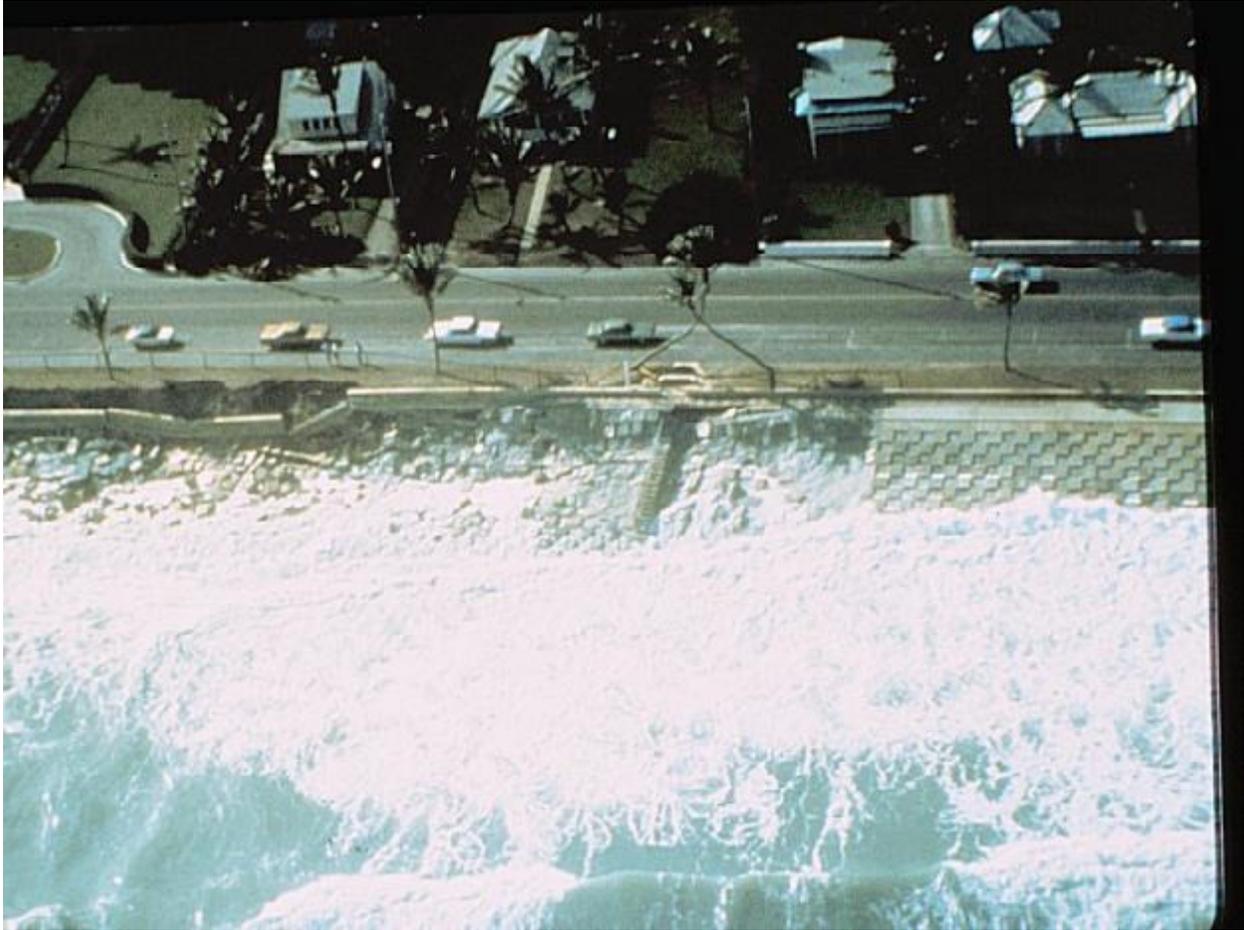
Early 1970s, aggravated erosion threatens multi-million dollar homes.



Aerial view of Delray Beach in June 1973. Atlantic Avenue (beach profile monument R180) is displayed in the center of the photograph.



Early 1970s, in response to erosion problems the City decides to build a beachfront revetment. The beachfront avenue is temporarily protected by there is no more recreational beach for the city.



Early 1970s, one year post-construction the revetment is severely damaged by storms and shows massive structural failure.



Delray Beach during construction of the first beach nourishment project in July 1973.



Aerial photo of the post-construction beach in September 1973 with Atlantic Avenue (R180) in the center of the photograph. A wide beach platform was built but no dune and dune vegetation were implemented at the time.



Cutterhead dredge working offshore of Delray Beach for one the renourishment projects.



Machinery works on the beach to connect the pipeline segments while offshore dredge and support vessels can be seen in the top right section of the photograph. This is from the 1984 beach renourishment project.



Aerial view of the 1992 Delray Beach renourishment project during construction.



Beach view of the 1992 beach renourishment project, dredge is offshore in the top left, machinery distributes the sand on the beach and surveyors verify the elevation of the fill.



Three pictures of the same segment of Delray beach around beach profile monument R181. Pre-construction (top left), immediately after construction (bottom left) and in 2001, showing a wide beach and a complete restoration of dune and dune vegetation.



Strong swells during Hurricane Isabel in 2005 make local surfers happy. The fully restored Delray Beach weathers well the effect of this and other storms in the extremely active 2005 Hurricane Season.



View from the beach, looking south, around beach profile monument R180, October 2005.



Aerial photography taken during construction of the 2002 beach renourishment project.



Delray Beach, view from beach front road A1A near profile monument R182, December 2012.



Delray Beach, view from beach front road A1A near profile monument R180, March 2015.

ABOUT THE AUTHOR

Lindino Benedet is currently the director of the Coastal & Marine Services Business line for CB&I and works out of the CB&I office in Boca Raton, FL and is responsible for CB&I offices in different locations of the USA and Brazil that perform coastal engineering, marine geosciences and marine environmental work. Lindino comes from a family with tradition in retail businesses, he owned and managed his own small retail business while attending high school, then went to university where he obtained his undergraduate degree at UNIVALI in Brazil in the year of 1999, majoring in Sciences-Oceanography, received his master's degree at Florida Atlantic University in Marine Geology in 2001 and obtained an MBA from the Executive MBA program at Fundação Dom Cabral in Minas Gerais, Brazil in 2013. Lindino is in the editorial board of shore & Beach and the Journal of Coastal Research and has published many scientific articles, presented in several international conferences and participated in many coastal engineering and marine geosciences consulting work since obtaining his bachelor's degree in 1999. Outside of work his hobbies include an enthusiasm for skateboarding and surfing, value investing, gourmet cooking and wine.

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Editorial Boards

Journal of Coastal Research, ISSN 0749-0208

Shore & Beach, Quarterly Journal of the American Shore & Beach Preservation Association (ASBPA)

ACKNOWLEDGEMENTS

First I would like to acknowledge my “better half”, Raquel, and our “little one”, Carolina, for the love and caring, for all the help during this process, and for their patience and understanding during many long nights and weekends sacrificed in the production of this work. My gratitude and love for my family can never be properly expressed in words, I love you.

Many thanks to my promoter Marcel Stive for his guidance, support and friendship. Marcel is a role model for all coastal engineers worldwide but his humbleness never ceases to amaze me. During this process where I learned to admire Marcel, the coastal engineer, but most important, I became good friends with Marcel and his family and that friendship I will cherish forever.

Thanks to the thesis committee that took time out of their difficult and extremely busy schedules to help me with this thesis, your inputs are very much appreciated.

Many thanks to Antonio Klein and Charlie Finkl. Their collaboration in co-authorship of manuscripts, general guidance and support and most important, the continuous questions they posed such as: “when are you going to finish it?”, “do you need any help?” Pushed to continue to work on my PhD in the midst of multiple changes of countries, bosses and jobs.

Thanks to the city of Delray Beach for the data of the continuous monitoring program, the Delray Beach nourishment program is a great success and brought immense benefits to the city. We are only trying to make it even better.

Thanks to the team of *Coastal Planning and Engineering Inc.*, who became the Shaw Group and then CB&I in 2013. The name of the company changed, but the people are the same and I would like to thank all my colleagues for all the interesting discussions on coastal processes and friendship over the years.

Many Thanks to my colleagues at TU Delft and Deltares who encouraged me to engage in this journey and that have contributed to the publications as co-authors, reviewers or brainstormers over the years. Special thanks to Ad Reniers for supporting this work from start to end, it was good to meet you in our kick off meeting in Florida in ‘day 1’ and it is an honor to have you as co-promoter

to close this journey and DJ who provided critical guidance in the Delft3D model and insightful discussions and reviews of manuscripts.

Lastly, but definitely not least, special thanks to my mother, to whom I own what I am.

PROPOSITIONS:

Hot spots can be identified and solutions to reduce hot spot losses can be designed – this thesis.

The volume losses of the Delray Beach nourishment program can be cut in half. Highland Beach may not be too happy about it, but they should not be too upset - this thesis.

Big holes on the seabed (dredge pits) can be used for coastal protection in a similar way as breakwaters are used – this thesis.

Erosion cold spots can occur in wave focusing zones and hot spots can occur in wave shadow zones – this thesis.

One-line shoreline models driven by waves and empirical transport formulations cannot forecast shoreline change when gradients in wave height are important.

The Beach Nourishment design practice in the USA has evolved tremendously over the years, but more attention should be given to the random nature of beach and dredge pit sampling.

Beaches will always need sand because humans need water, power and international trade.

Many times the answers are right in front of us, but we can't see it because we are blinded by political-economic constraints or by what we think the answers are.

Brazil needs massive reforms in tax, labor, legal and government systems to function in a globalized world; it will be a challenge for the country to recover from the current situation.

All you can do is the best you can with the time you have.