UNIVERSIDADE FEDERAL DO RIO GRANDE
INSTITUTO DE OCEANOGRAFIA – IO

Programa de Pós-Graduação em Oceanografia Física, Química e Geológica

Quantificação da Influência da Geomorfologia e Urbanização no Recuo da Linha de Costa em Cenários de Elevação do Nível do Mar

Ana Paula Piazza Forgiarini

Dissertação apresentada ao Programa de Pós-Graduação em Oceanografia Física, Química e Geológica, como parte dos requisitos para a obtenção do Título de Mestre.

Orientador Dr. Lauro Júlio Calliari.
Co-orientadoras: Dr.ª Salette A. de Figueiredo, Dr.ª Elaine S. Goulart.

Rio Grande
Março, 2019

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"... mas se o mar praticasse selvagerias ou crueldades era só porque não podia evitá-lo."

H. Hemingway – O Velho e o Mar

AGRADECIMENTOS

Gostaria de agradecer enormemente a todas as pessoas que me ajudaram de alguma forma durante a caminhada do mestrado. O caminho às vezes pode ser um pouco tortuoso e difícil de percorrer, mas a satisfação da chegada e as experiências ao longo da caminhada são enormes e enriquecedoras, principalmente quando se caminha acompanhado.

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RESUMO

A zona costeira é um sistema dinâmico extremamente susceptível às variações nas forçantes externas em diversas escalas, que vão desde elevação na altura de ondas gerando eventos erosivos pontuais em questão de dias, até grandes variações no nível do mar e alcance dos efeitos erosivos que podem causar recuo ou avanço na linha de costa ao longo de dezenas até milhares de anos. A forma como a costa irá responder a estas variações irá depender das particularidades geomorfológicas de cada região. Com o efeito das mudanças climáticas, é esperado que as linhas de costa modifiquem sua morfodinâmica em função da alteração dos regimes de ondas, do aumento dos eventos erosivos trazidos por tempestades, da modificação das taxas sedimentares entre outras consequências. Maior atenção deve ser dada aos locais em que os fenômenos erosivos afetam diretamente as zonas urbanas. O Balneário Hermenegildo foi escolhido como área de estudo, uma vez que permite entender as diferenças na evolução da linha de costa em trechos urbanizados e trechos sem ação antrópica significativa, e principalmente permite a quantificação da influencia antrópica no recuo da linha de costa do local. O estudo ocorreu através da simulação da evolução costeira em escalas de interesse ao gerenciamento costeiro, utilizando um modelo de resposta estocástica que considera incertezas relacionadas aos principais parâmetros que influenciam as modificações da LC, tais como balanço sedimentar e nível do mar, buscando subsidiar o futuro gerenciamento costeiro do local, que historicamente sofre com graves problemas erosivos. O levantamento topográfico da área ocorreu através da utilização de um drone, para consequente geração do substrato (perfil topo-batimétrico) do local que serviu de *input* para o modelo. O teste estatístico Kruskal-Wallis foi aplicado para verificar as diferenças entre as distribuições de recuos da linha de costa obtidos, isolando os efeitos dos parâmetros geomorfológicos costeiros (dunas e urbanização). O trabalho permite concluir que a morfologia dos campos de duna da região estudada não contribui significativamente com as distancia de recuo da linha de costa do local, ao contrario da presença de estruturas rígidas e urbanização que significativamente afeta o recuo da linha de costa do local. As projeções da linha de costa para 2040 mostram que a área urbana apresentou as maiores taxas de recuo em todas as simulações, com um recuo médio de 159 m (7.57 m/ano), enquanto os campos de dunas sul e norte mostraram 77.7 m (3.7 m/ano) e 81.3 m (3.87 m/ano) de recuo médio da linh de costa. Para as projeções de2100, a área urbana apresentou recuo médio de 716 m (8.83 m/ano), enquanto os campos de dunas do sul e do norte mostraram 358.2 (4.42 m/ano) e 366.1 m de recessão (4.51 m/ano).

ABSTRACT

The coastal zone is a dynamic system extremely susceptible to variations in external forcing at various scales. The way the coast will respond to these variations will depend on the geomorphological particularities of each region. With the effects of climate change, the coastlines

are expected to modify their morphodynamic due to the alteration of the wave regimes, the increase of the erosive events brought by storms, and the modification of the sedimentary rates among other consequences. Greater attention should be given to sites where erosion affects directly urban areas. Hermenegildo Beach was chosen as study area, since it allows understanding the differences in coastline evolution in urbanized stretches and stretches without significant anthropic action, and mainly allows the local quantification of the anthropic influence in coastline retreat. The study was carried out through the simulation of coastal evolution in management scales, using a stochastic morpho-kinematic model that considers uncertainties related to the main parameters that influence the coastline modifications, such as sedimentary balance and sea level, hopefully subsidizing the future management of the site, which historically suffers from severe erosion problems. The topographic data was collected by a drone survey, for the creation of the local substrate (topo-bathymetric profile). A Kruskal-Wallis test was applied to test the differences in the entire distributions of coastal recession from the simulation results among sectors, isolating the effects of onshore geomorphological parameters (dune morphology or absence of urbanization). We concluded that dune morphology do not significantly influence coastal recession at Hermenegildo Beach. However, the presence of rigid coastal structures in the urbanized sector significantly affects coastal recession in comparison to non-structured dune fields for both time horizons considered. The 2040 coastline projections show that the urban area presented higher recession rates among all the simulations with a mean recession of 159 m (7.57m/year) while the southern and northern dune fields showed 77.7 m (3.7 m/year) and 81.3 m (3.87 m/year) of mean coastline recession. For 2100 projections the urban area presented a mean recession of 716 m (8.83 m/year), while the southern and northern dune fields showed 358.2 (4.42 m/year) m and 366.1 m of recession (4.51 m/year).

Lista de ilustrações da dissertação

Lista de ilustrações do artigo

Lista de tabelas do artigo

Lista de Equações do artigo

SUMÁRIO

CAPÍTULO I

1. Introdução

Caracterizando-se como um sistema de interface entre continente e oceano, a zona costeira apresenta-se extremamente dinâmica e susceptível aos fenômenos que nela ocorrem, inevitavelmente alterando sua resposta morfodinâmica após qualquer estimulo natural ou antrópico (Carter & Woodroffe, 1994). Devem-se destacar nesses processos as costas arenosas que correspondem a 31% das praias mundiais (Luijendijk et al., 2018). A costa apresenta diferentes configurações fortemente dependentes de escalas temporais e espaciais, configuração geomorfológica, tipo e disponibilidade de sedimento, regime de ondas incidentes, correntes e elevação do nível do mar (Roy et al., 1994). Os efeitos das mudanças climáticas globais são ainda mais danosos nas costas arenosas que apresentam urbanização, onde por vezes a proteção natural das dunas encontra-se parcialmente ou até completamente suprimida pelo avanço das construções.

Em resposta ao aumento das emissões de gases estufa para a atmosfera, e consequentemente o aumento da temperatura global, o relatório de 2013 redigido pelo Painel Intergovernamental para as Mudanças Climáticas (IPCC) afirma que o clima mundial está sem duvidas mudando. Essas mudanças irreversíveis causam um crescente número de danos aos ambientes, trazidos em consequência da descaracterização dos eventos meteo-oceanográficos como um todo, dados, por exemplo, pelo aumento do nível do mar, da temperatura e precipitação, pela intensificação dos ventos, marés meteorológicas e aumento da ocorrência de eventos extremos entre outros (Fitzgerald et al., 2008).

Os episódios de níveis extremos de elevação do mar têm aumentado a partir de 1970 (IPCC, 2013). Em decorrência disso, o balanço sedimentar negativo nas zonas costeiras pode ser incrementado, impactando a resposta das feições topográficas da costa compreendidas entre a retrobarreira (porção mais continental da zona costeira) e a antepraia (limite de máxima extensão da praia subaquosa) (Fitzgerald et al., 2008). Apesar do impacto inevitável dos efeitos das mudanças climáticas na zona costeira, o grau de reação da Linha de Costa (LC) a esses efeitos é fortemente dependente das características inerentes de cada região, que apresentam diferentes respostas, como aponta Figueiredo (2018). Para os estudos de evolução costeira, caracterizados pela investigação do comportamento da LC, três principais fatores devem ser considerados: as variações do nível do mar, o balanço sedimentar de uma região e sua geomorfologia (Carter & Woodroffe, 1994).

As variações do nível do mar apresentam um grande consenso quanto sua existência e aos efeitos trazidos à zona costeira, porém como demonstram Roy et al. (1994), durante períodos de lenta variação do nível do mar, os efeitos do balanço sedimentar são mais importantes para o deslocamento da LC do que as próprias variações no nível da água. Atualmente, o cenário de mudanças climáticas ainda apresenta essas pequenas variações, sendo que as taxas globais de aumento do nível do mar retratam um incremento de 2 mm/ano (IPCC, 2013), apontando o balanço sedimentar como principal controlador da região costeira.

A erosão costeira, que afeta mundialmente 24% das praias arenosas (Luijendijk et al., 2018), caracteriza-se pelo déficit sedimentar de uma determinada área (Bird, 2008). Esta é desencadeada por fatores antrópicos, *e.g.* fixação da LC por estruturas rígidas e construção de balneários; ou naturais e.g. déficit sedimentar. A erosão costeira promove o recuo da LC, sendo o estudo da mesma importante item para o gerenciamento das zonas costeiras.

Cowell & Kinsela (2018) mostram que, apesar de ter influência secundária nas variações da LC em relação à dinâmica da antepraia, a morfologia das feições topográficas costeiras desempenha um papel relevante nas trocas sedimentares entre esses dois setores, induzindo diferentes ajustes morfodinâmicos da zona costeira com base em suas características sedimentares. As feições topográficas costeiras, *e.g.*, campos de dunas, podem suprir ou não a demanda sedimentar da antepraia na busca de um perfil de equilíbrio, caracterizando um estado de acresção/neutralidade ou erosão das LC, respectivamente (Roy et al., 1994).

Algumas incertezas estão relacionadas às investigações das variações da LC, conforme as mesmas são afetadas pelas mudanças climáticas (Cowell et al., 2002). Como explicado por Cowell et al. (2006) essas incertezas surgem de três principais fontes: 1) incertezas relacionadas às próprias mudanças climáticas; 2) o efeito das mudanças climáticas no aumento do nível do mar; e 3) a modelagem dessas incertezas nas variações da LC.

A isso, Terwindt & Battjes (1991) agregam ulteriores dúvidas, mostrando a dificuldade de se determinar precisamente parâmetros relevantes para as modificações de larga escala. Muitos obstáculos são encontrados para obter uma quantificação exata para cada parâmetro que influencia nas variações da LC, principalmente se pensarmos em escalas maiores de tempo (de décadas a centenas de anos) e espaço (dezenas de km). Por esse motivo ainda, é extremamente complexo estabelecer as relações e influências das modificações de curta escala, nas de maior escala.

Os estudos costeiros de longo termo apresentam-se interessantes ferramentas a serem utilizadas pelos gestores costeiros, uma vez que permitem prever possíveis alterações morfodinâmicas significativas, em escalas onde é possível atuar na prevenção dos efeitos negativos das variações costeiras, sendo possível associar para cada escala espaço-temporal os principais parâmetros dominantes nas variações costeiras como mostrado pela Fig. 1.

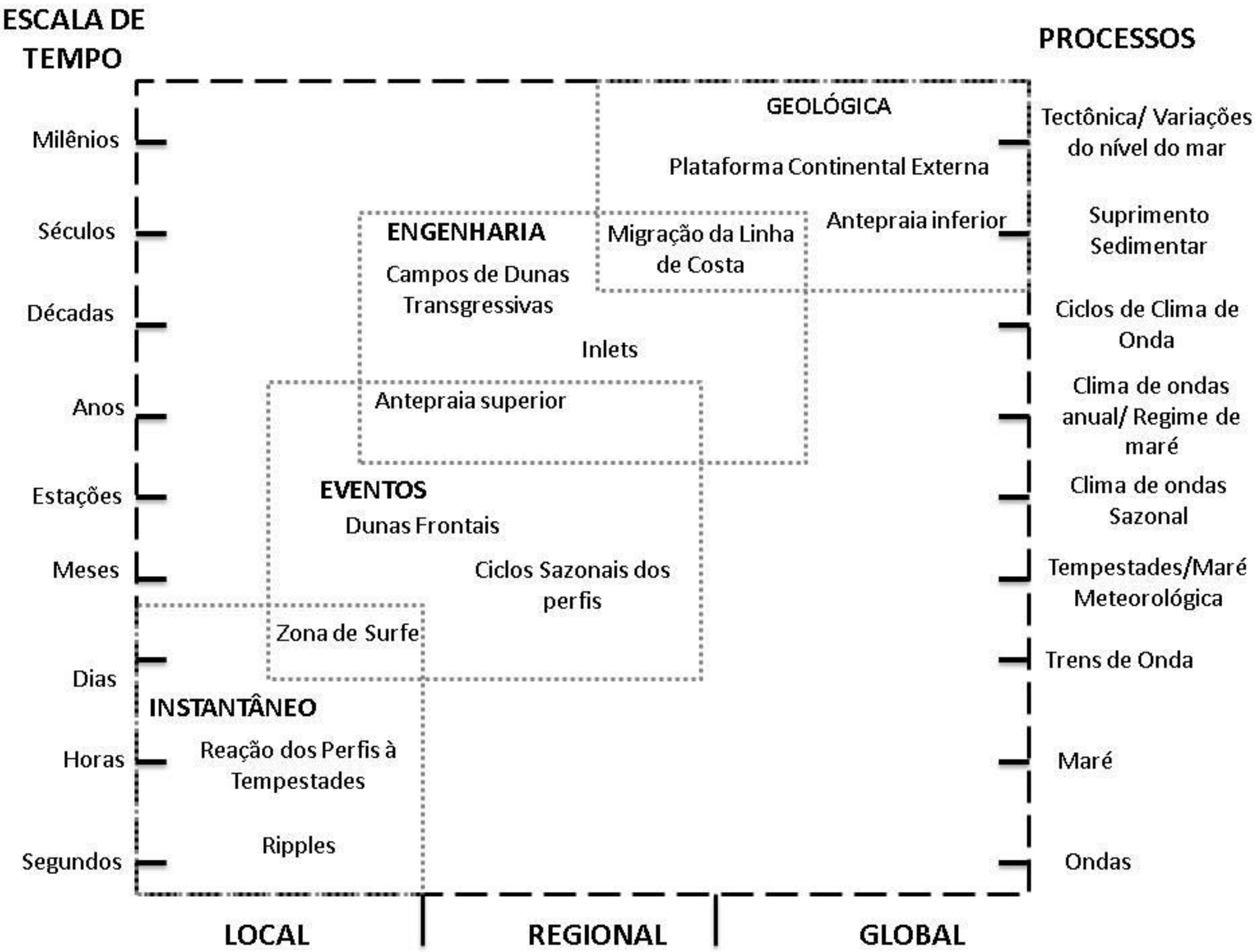

Figura 1 - Processos dominantes que influenciam as variações da linha de costa em diferentes escalas espaço-temporais. Modificado de Albuquerque, 2013.

O litoral brasileiro caracteriza-se por uma costa predominante neutra, onde os processos erosivos se sobressaem aos processos de progradação (Muehe, 2006). Os principais fatores que levam o litoral brasileiro à erosão são: a interferência humana sobre os processos costeiros e sua atuação na urbanização da orla, e a falta de suprimento sedimentar na costa.

Para a costa do RS Toldo Jr. et al. (2005), apontam em uma série histórica de 22 anos analisados, que mais de 70% da região costeira exibe um caráter erosivo, mostrando taxas de recuo da LC de cerca 4,45 m/ano.

Inserido nesse contexto, o Balneário Hermenegildo, RS, se apresenta como uma área de estudo interessante no que diz respeito às variações dos perfis praiais, uma vez que no mesmo desenvolvemse trechos antropizados e trechos sem expressiva influência humana (campos de dunas), caracterizado por um perfil erosivo. O presente trabalho aborda uma investigação sobre a influência das variações topográficas e devido à urbanização nas modificações da LC, considerando a influência do aumento do nível do mar em escala local.

Apesar de ter esforços globais investigando as causas e o risco trazido pelas mudanças climáticas para a zona costeira, a falta de estudos quantitativos em relação aos efeitos do aumento do nível do mar constitui uma lacuna relevante a ser preenchida para melhor compreendermos os efeitos erosivos trazidos à zona costeira. A fim de entender como cada região é afetada pelo aumento do nível do mar, é imprescindível que as características geomorfológicas, sedimentares e a influência humana sejam investigadas em escalas locais (Le Cozannet et al., 2014).

Para dar maior transparência e melhor assessorar o gerenciamento costeiro do local, modelos estocásticos são uma importante ferramenta de investigação, apresentando distâncias de recuo ou acresção da linha de costa na forma de probabilidade de risco, permitindo aos gestores a escolha de piores ou melhores cenários, a fim de prevenir o risco costeiro associado ao aumento do nível do mar em locais potencialmente ameaçados. Para o trabalho foi utilizado um modelo morfo-comportamental estocástico desenvolvido por Cowell et al., (1992), de forma a compreender escalas interessantes para o manejo costeiro (anos de 2040 e 2100).

O presente trabalho tem como objetivo geral avaliar a resposta costeira em setores com diferentes configurações morfológicas, ao aumento do nível do mar no Balneário Hermenegildo. Para alcançar esse fim o trabalho projeta as futuras LC para os anos de 2040 e 2100, considerando as características geomorfológicas de diferentes setores, no Balneário Hermenegildo. Além disso, a quantificação da influência da urbanização e da topografia dos campos de dunas do local permitiu mostrar o impacto causado pelo homem no recuo da LC, durante o aumento do nível do mar, em um local historicamente erosivo.

2. Caracterização Regional

2.1 Localização da Área de estudo

O Balneário Hermenegildo é parte do Município de Santa Vitoria do Palmar e localiza-se no extremo sul do Rio Grande do Sul a 10 km da fronteira com o Uruguai (Fig. 2). O Balneário pode ser dividido em três partes principais (Fig. 3): 1) campo de dunas sul; 2) área urbanizada; e 3) campo de dunas norte. Os campos de dunas ao sul diferenciam-se ligeiramente pela presença de dunas mais vegetadas e com maiores alturas, sendo a influência humana pouco percebida, a não ser pelas numerosas trilhas e marcas de veículos no pós-raia e nas próprias dunas que, de forma geral, ocorrem em todo o balneário. Os campos de dunas ao norte do balneário mostram-se pouco desenvolvidos, apresentando grandes quantidades de lixo e restos de construções, da região urbanizada, erodidas pelas ressacas.

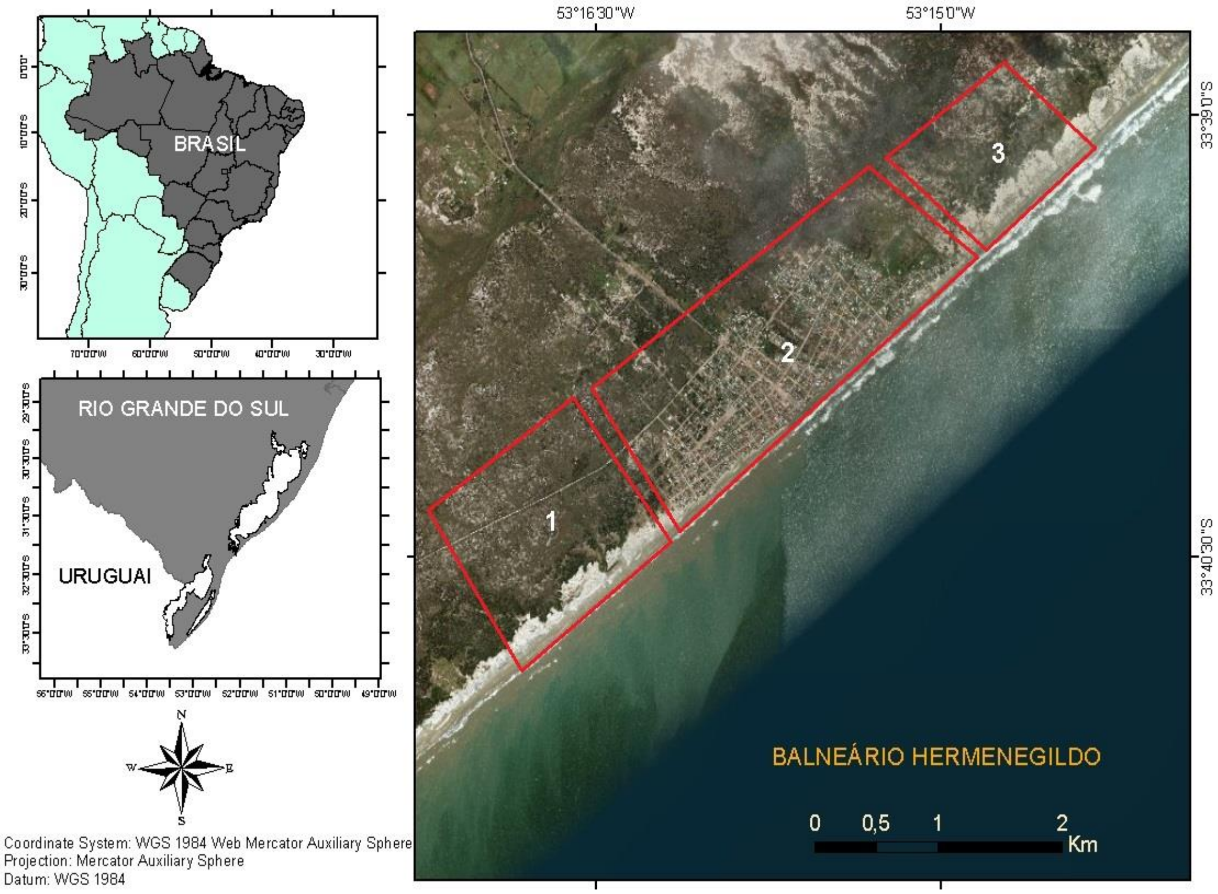

Figura 2 - Mapa da localização da área de estudo. 1) campo de dunas sul; 2) área urbana; e 3) campos de dunas norte.

A área urbanizada apresenta diversas estruturas de contenção associadas à tentativa de barrar os efeitos erosivos das marés meteorológicas no local, que surtem pouco efeito e acabam agravando o problema erosivo no local. Segundo Oliveira et al. (2018) o balneário passou por intensas mudanças desde a ocorrência das primeiras ocupações, que já em 1947 se localizavam na faixa de dunas frontais do local. Ainda segundo o mesmo estudo, com o aumento da urbanização sobre o cordão de dunas frontais observa-se a gradual diminuição do mesmo, agravando intensamente os efeitos erosivos no local. Na tentativa de conter o avanço da maré meteorológica, podem ser encontrados no balneário diferentes métodos de proteção costeira, como muros de contenção de cimento ou de madeira, sacos de areia, enrocamentos e pneus (Fig. 4).

Figura 3 - De cima para baixo: extremo norte do balneário com dunas incipientes e ação antrópica moderada. Zona urbanizada. Extremo sul do balneário com dunas bem desenvolvidas e vegetadas. Fontes: Elaine S. Goulart (norte e sul do balneário); Ulisses de Oliveira.

O número de lotes que apresentam estruturas de contenção, entre 2009 e 2016 aumentou em 20%, passando de 50 a 70% (Oliveira et al., 2018), sendo porém ineficazes contra o avanço do mar trazendo enormes prejuízos sociais e econômicos no local (Esteves et al., 2001, Koerner, 2012).

Figura 4 - Detalhe das numerosas estruturas de contenção na parte urbanizada do balneário. 20/11/2017.

2.2 Caracterização geomorfológica

A planície costeira do RS (PCRS), de orientação SO-NE, é formada pela justaposição de depósitos sedimentares oriundos do retrabalhamento de leques aluviais ao longo dos ciclos quaternários de transgressão e regressão marinha (Villwock & Tomazelli, 1995). Esses ciclos possibilitaram a formação de quatro sistemas do tipo Laguna-Barreira, nomeados de I a IV partindo do mais antigo (Fig. 2), sendo o sistema IV a atual LC holocênica. O cordão litorâneo apresenta em muitas partes o recobrimento de extensos campos de dunas, que progradam sobre banhados e os conjuntos de lagoas e lagunas costeiras (Villwock, 1984). A PCRS apresenta um caráter oceânico aberto, mostrando uma grande influência das ondas, ventos e correntes litorâneas no molde de sua morfologia.

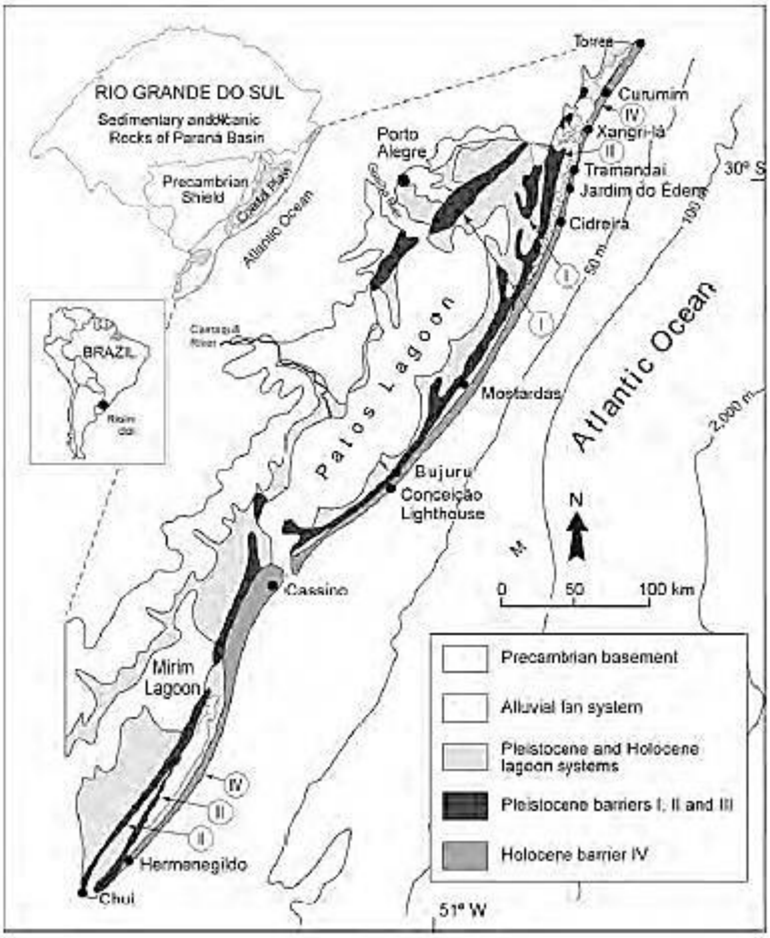

Figura 5 - Características geomorfológicas da costa do RS. Extraído de Dillenburg et al., 2009.

Dillenburg et al. (2009) mostram que os 640 km litorâneos do RS dividem-se entre sutis embaiamentos e projeções (Fig. 5). De forma geral, os embaiamentos apresentam características acrescivas, enquanto as projeções características predominantemente erosivas. Essas variações no regime deposicional devem-se principalmente as diferentes características da antepraia adjacente a essas feições. A mesma configura-se mais íngreme a frente das projeções e mais suave nos embaiamentos, criando um gradiente lateral de energia de onda, que acaba promovendo a erosão nas projeções e o consequente transporte sedimentar para os embaiamentos (Dillenburg & Hesp, 2009).

A PCRS é composta por diversos corpos lagunares. Ao norte podem-se encontrar pequenas lagoas costeiras, na porção central a Lagoa dos Patos mais interiorizada e as menores lagoas do Peixe e do Estreito; Na porção Sul da PCRS enfim, a Lagoa Mirim conectada com a Lagoa Mangueira através do banhado do Taim. Essas lagunas e lagoas acabam retendo toda a contribuição sedimentar oriunda do continente, deixando à LC apenas a contribuição sedimentar marinha e eólica (Buchmann et al., 2009) .

O Balneário Hermenegildo localiza-se na porção sul de uma projeção costeira no RS, sofrendo, portanto com a erosão característica dessas feições. Isso é também mostrado no estudo de Dillenburg et al. (2000) que apresentaram para o trecho uma tendência erosiva desde 7ka até o presente. O Balneário Hermenegildo situa-se na Barreira IV com alguma exceção ao sul do mesmo, onde a barreira III aflora devido a continua erosão no local (Lima, 2013).

2.3 Caracterização meteo-oceanográfica

A região costeira do RS apresenta-se dominada por ondas, uma vez que o regime de micromaré, de acordo com o sistema de classificação de Davies (1964), caracteriza-se por 0.47 m de elevação média ao longo de toda a costa (Möller et al., 2001).

De acordo com Klein (1998), o vento predominante ao longo da costa rio-grandense sopra de NE, porém os ventos de SO trazem os sistemas frontais que favorecem o empilhamento da água na costa, aumentando o nível relativo do mar e promovendo a forte ocorrência de marés meteorológicas (ressacas), definidas por Pugh (1987) como a diferenças entre os níveis observados e a maré astronômica de um determinado local.

A região encontra-se dominada pela alternância de massa de ar vinculada ao Anticiclone do Atlântico Sul e o Anticiclone Migratório Polar, que permitem as diferentes características sazonais dos regimes de vento (Villwock & Tomazelli, 1995). Devido a essa configuração os ventos de nordeste predominam na maior parte do ano, enquanto os ventos de SO que trazem os sistemas frontais promovendo as fortes marés meteorológicas do local apresentam maior ocorrência durante os meses de inverno (Klein, 1998). A esse fatores, a baixa declividade da costa constitui mais uma forçante no estabelecimento do domínio por ondas, que se elevam em média entre 1 e 1.5 m de em toda a região (Cuchiara et al., 2005), fortemente impactando as variações da LC.

Apesar da menor frequência de ocorrência dos ventos de SO, o transporte longitudinal de sedimentos pelas correntes litorâneas se dá predominantemente em direção NE, uma vez que os mesmos causam a incidência obliqua na costa de ondas do quadrante S responsáveis por até 30% do transporte sedimentar total (Lima et al., 2001).

Os efeitos erosivos da maré meteorológica são fortemente sentidos no Balneário Hermenegildo, de orientação NE e praia intermediaria (Calliari & Klein, 1993). A maré meteorológica incide quase que ortogonalmente à LC, e aliada a um pós-praia estreito e de baixa declividade (Calliari & Klein, 1993) constitui o fator dominante da erosão no local. Dependendo da intensidade do vento e da ocorrência de eventos extremos, a maré meteorológica pode atingir no local elevações entre 2 e 5 m, sendo influenciada em 43% pelo efeito dos ventos, 35% pela ondulação, 15% pela maré astronômica e 7% pela pressão atmosférica (Maia et al., 2016).

O local é fortemente afetado por eventos erosivos (Fig. 6) devido a seu posicionamento na linha de costa e aos processos oceanográficos que ocorrem no lugar. Agravando ainda mais a situação erosiva do local, assim como a região do Farol da Conceição, localizado no litoral médio do RS, o Balneário Hermenegildo se caracteriza como um local onde a energia de ondas é concentrada na costa, devido à refração das ondas nas feições da plataforma continental, promovendo hot spots erosivos em ambos os locais (Speransky & Calliari, 2006).

Figura 6 - Erosão no Balneário Hermenegildo, destruindo as estruturas de contenção, causando danos socioeconômico e ambiental. Foto: Salette A. de Figueiredo. 20/11/2017.

Além disso, no local o sedimento transportado pela deriva litorânea, é trapeado nos promontórios uruguaios, que não permitem a chegada do mesmo no balneário, contribuindo para o balanço sedimentar negativo do local (Lima et al., 2013).

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CAPÍTULO II - ARTIGO

QUANTIFYING THE GEOMORPHOLOGIC AND URBANIZATION INFLUENCE ON COASTAL RETREAT UNDER SEA LEVEL RISE

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Abstract

In response to increasing greenhouse gases emissions in the atmosphere and rise in global temperatures, global climate is undoubtedly changing, resulting in increasing impacts on the environment. Mean global sea level rates are currently increasing, although presenting regionally specific trends. Coastal erosion and flooding can be accelerated by the effects of the changing climate, incising beach protection features, such as foredunes, thus endangering the population living along the coastal fringe. Many uncertainties remain regarding the coastal response to sea level rise; coastal geomorphology (topography, bathymetry, and sediment texture) plays a relevant role in the manner sediment exchanges occur, inducing different morphodynamic readjustments. This study aimed to investigate the influence of coastal topography and urbanization under regionally accelerated rates of sea level rise and project the future coastline position for 2040 and 2100 at Hermenegildo Beach, using a stochastic morpho-kinematic model (the Random Shoreface Translation Model). Nonetheless, differences in dune height between the dune fields sectors of Hermenegildo Beach do not significantly influence the mean coastal retreat (1.98%). When comparing the mean coastal recession results for the site's urban area with and without rigid structures and paving, we conclude that the presence of rigid structures contributed to an increase of 13.52% in mean coastal recession. A Kruskal-Wallis test was applied to test the differences in the entire distributions of coastal recession from the simulation results among sectors, isolating the effects of onshore geomorphological parameters (dune morphology or absence of urbanization). We concluded that dune morphology do not significantly influence coastal recession at Hermenegildo Beach. However, the presence of rigid coastal structures in the urbanized sector significantly affects coastal recession in comparison to non-structured dune fields for both time horizons considered. The 2040 coastline projections show that the urban area presented higher recession rates among all the simulations with a mean recession of 159 m (7.57m/year) while the southern and northern dune fields showed 77.7 m (3.7 m/year) and 81.3 m (3.87 m/year) of mean coastline recession. For 2100 projections the urban area presented a mean recession of 716 m (8.83 m/year), while the southern and northern dune fields showed 358.2 (4.42 m/year) m and 366.1 m of recession (4.51 m/year).

Keywords: *Erosion; dune; rigid structures; climate change; RanSTM model; Brazil, Rio Grande do Sul, Hermenegildo Beach.*

1. Introduction

In response to increasing greenhouse gas emissions to the atmosphere and the rise in global temperatures, the 2014 report by the Intergovernmental Panel on Climate Change (IPCC) states that global climate is undoubtedly changing. These irreversible changes are causing an increasing number of impacts to the environment as a result of the intensification of meteo-oceanographic events. The increase in sea level, temperature, and precipitation; wind intensification, storm surges; and increased occurrence of extreme events are some phenomena resulting from such climatic changes (Fitzgerald et al., 2008).

Episodes of extreme sea level rise, for example, during storm surge events, have increased in frequency since 1970 (IPCC, 2014). Along with long-term negative or reduced sediment supply and storms, sea level rise can cause beach and foredune erosion along barrier coasts (Fitzgerald, 2008).

Currently mean global sea level rates are increasing, although accurate regional rates for coastal applications rely on local wind and wave regimes and tectonic uplift/subsidence, as noted by Nicholls (2010).

Despite the inevitable impacts of climate change on the coastal zone, coping with regional variations in sea level rise, as previously mentioned, via a coastal response to these effects is strongly dependent on the inherent characteristics of each region (Figueiredo et al., 2018). For long-term coastal evolutionary studies, characterized by the investigation of coastline behavior over decades to millennia, three factors are extremely relevant: sea level variations, regional sedimentary budget, and geomorphology (Carter & Woodroffe, 1994).

Sea level rise scenarios are widely accepted amongst scientists; however, their effects to the coastal zone will depend upon their rate and the relative importance to regional sedimentary budgets. As demonstrated by Roy et al. (1994), during periods of slow sea level change, sediment budget effects are more important in determining coastline position than the actual water level. Under the current sea level rise rates, with global sea level rates showing an increase of 2 mm/year (IPCC, 2014), in regions where the sedimentary budget shows great amplitude (positive or negative) it can dominate coastal change.

Coastal erosion affects 24% of sandy beaches worldwide (Luijendijk et al., 2018). It is, characterized by the sedimentary deficit of a given area (Bird, 2008) triggered by anthropic, *e.g., a* coastline with rigid structures and beachfront construction, or natural factors, *e.g.,* erosive storm surge events. Coastal erosion can be accelerated by climate change effects. This may lead to an increased occurrence of extreme events, promoting flooding and incising of beach protection features, such as foredunes, endangering the population living in the coastal zone (Simeoni & Corbau, 2009).

Terwindt & Battjes (1991) show the difficulty in precisely determining parameters relevant to large scale morphodynamic modifications. Many obstacles are encountered to obtain an exact quantification for each parameter that influences coastline variations, particularly if we consider larger time scales (from decades to hundreds of years) and extensions (tens of km).It is even more difficult to establish the relationships between short-period and extension modifications at a larger scale. Further uncertainties emerge related to sea level rise and its impacts on the coastal zone. As explained by Cowell et al. (2006), uncertainties in relation to coastline position in the future arise from three main sources: 1) uncertainties related to climate change itself, 2) the effect of climate change on sea level rise, and 3) modeling these uncertainties in coastline response at timescales relevant to climate change.

Long-term coastal studies present interesting tools to be used by coastal managers because they allow predicting possibly significant morphodynamic changes at scales in which it is possible to act to prevent the negative effects of the coastal variations.

The Brazilian coast is characterized by a predominantly neutral coastline, where erosive regions exceed those that are accretive ones (Muehe, 2006). The main factors causing erosion along the Brazilian coast are: 1) human interference in the coastal processes and their role in coastal fringe urbanization, and 2) the lack of sedimentary supply to the coast. Along the coast of Rio Grande do Sul (RS), Toldo Jr. et al. (2005) noted that more than 70% of the coastal region exhibited an erosive character, with erosional rates of 4.45 m / year. Although a global effort is being made, investigations of coastal erosion and flooding are principally focused on the magnitude of the effects caused by sea level rise and their associated socio-economic losses, not extensively quantifying these events at local scales by investigating the main influences of the physical coastal parameters related to them. The gaps in understanding the relative influential role of coastal geomorphology, sediment availability, human interference, and sea level change highlight the need for further investigation relying on observational and modelled data at a local scale (Le Cozannet et al., 2014).

Topographic data, however, is relatively easier to obtain, and in the context of changing climate, the specific onshore morphological characterization of an area must be considered, when evaluating coastline behaviour, once it can bring significant differences on coastline change rates.

In this context, Hermenegildo Beach, the southern end of RS coast, presents itself as an interesting study area for quantifying onshore morphological influence on coastline recession, with urban stretches and stretches without expressive human influence, characterized as a mainly erosive region.

Dillenburg et al. (2000) investigated the RS coastline applying the Shoreface Translation Model (STM, Cowell et al., 1992), by simulating its evolution during the late Holocene (7ka) demonstrating that gradients in shoreface morphology, between embayments and projections together with onshore sediment supply have controlled its evolution.

The present article is focused in quantifying the influence of coastal morphology and urbanization in coastline response, under sea level rise scenarios at a local scale (Hermenegildo Beach). The study was conducted using a morpho-kinematic model the Random Shoreface Translation Model developed by Cowell et al. (1992), to investigate the main differences in coastline response driven by different geomorphological characteristics of the onshore topography and urbanization, at Hermenegildo Beach, at coastal management scale (2040 - 2100).

1.1 Regional Settings

The RS coast is a SW-NE oriented micro-tidal environment with a mean tidal range of 0.47 m, and is classified as a wave dominated coast (Calliari & Klein, 1993; Möller et al., 2001). According to Klein (1998), NE winds are dominant, but the occurrence of strong SW winds promote the rise in local sea level during storm surges (a maximum of 1.9 m according to Parise et al., 2009) that strike RS coast almost perpendicularly, increasing erosional effects. The undulating coastal barrier of the RS is divided into concave (coastal embayments) and convex segments (coastal projections), showing an accretive tendency in the coastal embayments and an erosive one in the projections. These differences are mainly because of differences in shoreface slopes, which, being steeper in the projections, and smoother in the embayments, leads to a lateral wave energy gradient, promoting sedimentary transport from the projections to the embayments (Dillenburg & Hesp, 2009; Martinho et al. 2009) following the main SW-NE littoral drift (Tomazelli & Villwock, 1992).

Hermenegildo Beach is in the final portion of a coastal projection of the RS (Fig. 1), though presenting erosional long-term characteristics of a transgressive barrier, as shown in the study presented by Dillenburg et al. (2000) who suggested an erosive tendency from 7 ka to the present.

The erosive effects from storm surges are acutely felt at Hermenegildo Beach, which shows a narrow backshore (Calliari & Klein, 1993) Depending on the intensity of the wind and the occurrence of extreme events can reach elevations between 2 and 5 m at the locality (Maia et al., 2016), promoting flooding in the urban area and washover of the dune fields.

Hermenegildo Beach, along with Conceição Lighthouse on another projection of the central coast of RS and 270 km from Hermenegildo, are characterized as erosional hot spots, where wave energy is magnified because of the coastal orientation toward the predominant wave direction and the refraction promoted by the features of the continental shelf that act as bathymetric lenses.

The urban expansion of Hermenegildo Beach was permanently established in 1950 and it's increasing to date as shown by Oliveira et al. (2018), weakening the natural protection once provided by foredunes. Thus, an anthropic erosional problem was introduced to the site, followed by coastline artificial restructuration, promoting an increase in the sedimentary deficit in the region, as seen by the more structured dune fields adjacent to the urbanization in comparison to the extreme erosion in the urban area. For this study, Hermenegildo Beach was divided into three stretches, as shown in Fig. 1 as the southern dune field, urban area, and northern dune field.

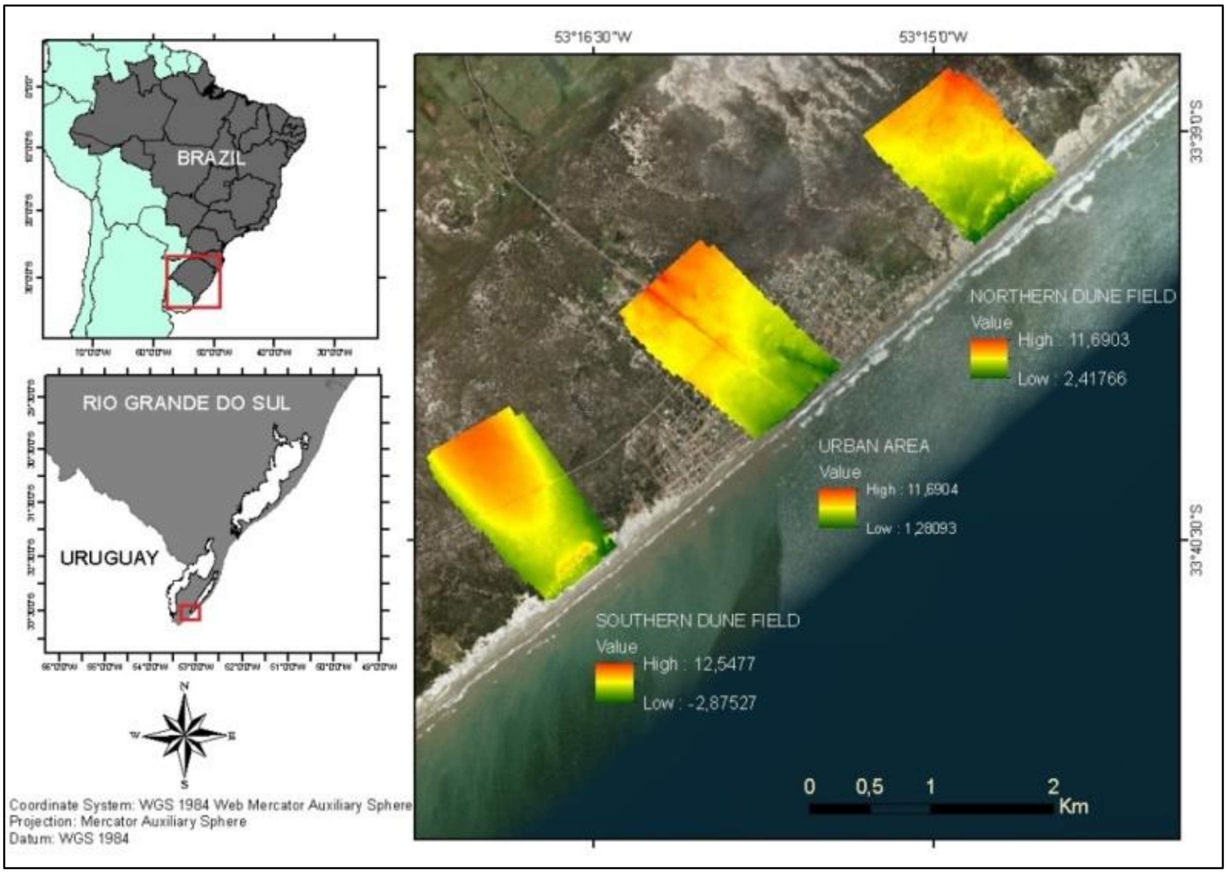

Figure 1. Map of the study area and its localization in Rio Grande do Sul (RS) state, Brazil. The coloured areas represent the DTMs obtained by the drone survey in the three study sites, for the creation of a mean topographic profile used a substrates for coastline projections.

The northern dune field is poorly developed and sparsely vegetated, presenting large amounts of anthropogenic debris including construction remains from the urbanized region eroded during storm surges. The southern dune field is slightly differentiated by the presence of more vegetated dunes of greater height, where the human influence is less perceptible, except for the numerous vehicle tracks on the backshore and dunes. The urbanized area presents several containment structures developed in an attempt to stop erosive effects from local storm surges, as well as some paved streets and residential houses. However, the containment structures are not particularly effective and probably aggravate the erosional problem (Esteves & dos Santos 2001; Koerner, 2012). Indication of localized erosion can also be seen in the peat outcrops and heavy minerals of the backshore (Calliari & Klein, 1993).

Several studies regarding coastline changes at Hermenegildo Beach note a general erosional tendency in the area. These include the study of Albuquerque (2013) using the change polygon method proposed by Smith & Cromley (2012), which identified in a 65-year time series (1947-2012) erosion rates of 1.68 m/year, with maximum rates recorded between 1996-2000 (6.29 m/year) and between 2005 and 2006 (5.25 m/year), coinciding with periods influenced by El Niño events. Retreat rates of 1.41 m/year were verified between 2010 and 2011. The author's shoreline projections are 8.18, 22.29 and 151.57 m of retreat for the years 2022, 2032, and 2100, respectively. Esteves et al. (2008), between 1999 and 2006, and Koerner (2009) presented historical retreat rates of 3.4 m/y and 1.21 m/y, respectively, for the locality. Comparisons made using sequential beach profiles by Machado et al. (2010), between 1996 and 2010, also confirmed a local sedimentary deficit of 134 m^3/year.

Figueiredo (2011) presented shoreline projections using the RanSTM model (Cowell et al., 1992), showing a mean shoreline retreat (50% probability) of 129 m, 358 m, and 521 m for the years 2030, 2070, and 2100, respectively, under a sea level rise scenario proposed by the fourth IPCC assessment report on climate change (IPCC, 2007 - AR4). However, in these simulations, the presence of local containment structures was not considered. Recently, Figueiredo et al. (2018) applied sea level projections provided by the most recent IPCC report (AR5, 2014) and obtained a mean retreat distance of 567 m for 2100 (6.5 m/year), slightly higher than those reported in her previous study, mainly because of the higher sea level rise rates used in the latter.

2. Methodology

In this section, we present a brief general scheme for the methodology used in this study, including all the steps from the field survey to the results. The scheme is shown in Fig. 2; each step will be further detailed in the following sections.

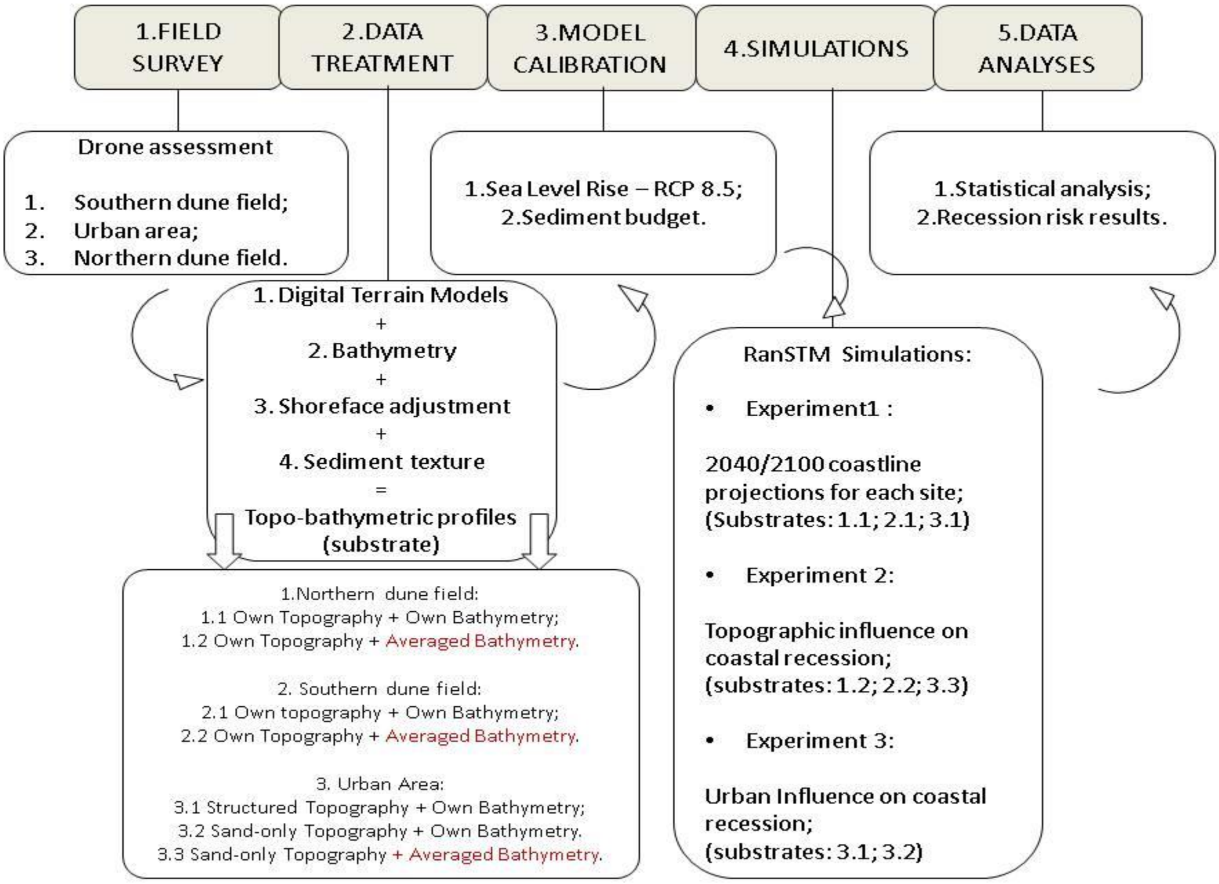

Figure 2. Methodological scheme.

2.1 The RanSTM Model

According to Dean & Maurmeyer (1983), some morpho-behavioral models were developed based on the assumption that they can deterministically predict the coastline evolution. These models are mainly based on Bruun's two-dimensional model (1962) that, predicts sedimentary changes only between the backshore and foreshore. This type of model presents some limitations mainly because it assumes extremely restricted input data conditions and, disregards any uncertainty attributable to sedimentary variations and sea level rise.

This restricted model calibration leads to uncertainty in the modeling results, which can be overcome by expressing the values of parameters and variables as probability distributions.

Stochastic models, such the RanSTM model used in this study, are able to transform uncertainties related to the input parameters in risk probability by assigning a probability density function (pdf) to each of the inputs to generate an output pdf. The RanSTM output provides a risk forecast of coastline displacement rather than a deterministic prediction, and it is obtained by repetitively running of different sets of sampled variates (geometric parameters and input values).

For each parameter permitted to vary during a simulation, its value is sampled by a pseudo-random generator, in the RanSTM case a congruential-generator.

Heuristic reasoning is used to determine the upper and lower boundaries, as well as internal division (e.g., average) values from which the random number will be developed.

The pdfs can be compiled using any data source, although the model expresses better results when compiled using hard data. The peak of each output distribution (the most probable value of a set of parameters or variables) corresponds to the calibrated estimate of the single parameter in a deterministic model.

The main advantage of forecasting using stochastic models is that they offer best estimates when compared to deterministic predictions, providing a measure for the risk of the estimates being wrong when in doubt or when lacking precise parameter values, thus supporting coastal managers with relevant information by presenting different hazard levels (Cowell et al., 2006).

For this study a limit of 1000 simulations was considered statistically ideal for the stochastic simulations of coastline variation, as presented by Carrasco & Chang (2005). Related to the concept of Large-scale coastal behavior (Terwindt & Battjes, 1991), the model simulates the behavioral variations of the coast from decadal to millennial scales. It simulates the horizontal and vertical displacement of a known substrate (topography, bathymetry and sedimentary texture) from its reworking by the sea level variations, redefining the new coastline position, as well as the geomorphological characteristics of the profile as a whole (from the backbarrier to shoreface), considering the topographic influences on the sedimentary changes, as well as the different response rates of the upper and lower shoreface (bathymetry) and its sedimentary accommodation space.

The main input data for the model are sedimentary budget, substrate (topography, bathymetry, and sedimentary texture), and sea level behavior (stable, rise or fall) along with its rates. Total coastal recession can be expressed as a function of several factors described in equation 1 as follows:

$$R(t) = \overline{R_v}\,(t) + \overline{R_{SL}}\,(t) \qquad (1)$$

Where, $R(t)$ is the total recession rate, $\overline{R_v}\,(t)$ is the recession rates associated to sediment deficit, $\overline{R_{SL}}\,(t)$ is the recession rate resulting from sea level rise.

2.2 Field Survey

Topographic surveys were used as a basis for substrate morphology and performed using a drone (*DJI Phantom 4*® model) and a Real Time Kinematics (RTK) GPS in the three sectors delimited for the study. Three Digital Terrain Models (DTMs) were created using Agisoft Photoscan™. The

DTMs were then processed in ArcGis™ following the step-by-step method of Daley (2005) to obtain a representative profile for each area to serve as the substrate morphology input for the model.

The survey resulted in more than 600 images with qualities of approximately 4 cm/px. Before each drone survey, targets were placed in the chosen areas and their positions were obtained using an RTK GPS for precisely georeferencing and establishing relative altitude values for each DTM. The processing used by the Agisoft Photoscan™ software is based on a structure-from-motion algorithm that, allows the reconstruction of the camera position and scene geometry by the identification of similar structures in each photograph (Westoby et al., 2012). The DTMs showed elevation errors of 4.48 cm for the southern dune field, 1.35 cm for the urban area, and 1.84 cm for the northern dune field.

The three areas extended 1 km inland and 500 m alongshore, as shown in Fig. 1, constraining parts of the urban area and, the southern and northern dune fields.

Before processing in Agisoft Photoscan™, all the altitude values were corrected using geoidal undulation (altitude differences between the ellipsoid and geoid), once the RTK GPS collects ellipsoids' relative altitudes, as the study was interested in orthometric altitudes. This was obtained through the Instituto Brasileiro de Geografia e Estatística (IBGE) website that offers an online service for geoid undulation corrections.

The current coastlines correspond to the foredune line, for the northern and southern dune fields, and the coastal structures for the urban area.

2.3 Bathymetric data

The input bathymetry used was extracted from Departamento de Hidrografia e Navegação, Brazilian Navy (DHN) charts available for the region that were previously digitized. The bathymetric profiles were processed in ArcGIS ™ following the same step-by-step cited in the field survey section, as described in Daley (2005), to obtain an average bathymetric profile for each area, allowing the formation of a single topo-bathymetric profile with the DTMs obtained during the previous stage. The Daley (2005) methodology is based on the Coastal–Tract concept (Cowell et al., 2003) that delimits coastal cells that present geomorphological similarities provided by sedimentary control and present the same coastal processes modifying them.

For general topographic and dune field influence quantification, an averaged bathymetry was created following Daley's (2005) methodology, considering the bathymetry from the three stretches altogether, to quantify the influence of onshore morphological variations on coastal recession rates by isolating this feature.

The four bathymetric profiles and respective Depths of Closure (DoC) are shown in Fig. 3.

2.4 Shoreface Adjustments

As input data the model requires the delineation of DoC (Hallermeier, 1980; Cowell et al., 1999) for the upper and lower shoreface, once they respond at different temporal scales to sedimentary exchanges. They play a fundamental role in the equilibrium profile of the coastal barrier, either serving as a sink or source of sediment. For the calculation of the DoC, two independent formulas were used for the upper (h_c – Equation 2) and lower (h_i – Equation 3) shoreface delineation, both extracted from Hallermeier (1980). For their calculation it is necessary to obtain 1) significant wave height, 2) standard deviation of the significant heights, 3) peak period, and 4) median sediment particle size (D_{50}) at 1.5 x h_c. The wave data were obtained from Laboratório de Análises Numéricas e Sistemas Dinâmicos (LANSD - FURG), which modeled 37 years of wave data in the Brazilian coast.

Shoreface textural data were obtained from Camargo (2012) who through the REMPLAC (Avaliação da Potencialidade Mineralógica da Plataforma Continental Jurídica Brasileira) program obtained and analyzed sedimentary samples of Hermenegildo Beach shoreface sediments.

The formulas from Hallermeier (1980) are as follows:

$$\boldsymbol{h_c = 2 * \overline{H}_{sig} + 11 * \sigma} \quad (2)$$

where,

h_c = upper shoreface DoC (m);

$\overline{H}_{sig}$ = mean significant wave height (m);

σ = standard deviation of mean significant wave height (m)

$$\boldsymbol{h_i = \left(\overline{H}_{sig} - 0.3 * \sigma\right) * T_{sig} * \left(\frac{g}{500 D_{50}}\right)^{0.5}} \qquad (3)$$

where,

h_i = lower shoreface DoC (m);

$\overline{H}_{sig}$ = *mean significant wave height (m);*

σ = *standard deviation of significant wave height (m);*

T_{sig} = *significant peak period (s);*

D_{50} = *median grain size at 1.5 *hc;*

The depth differences are provided from the different granulometries along the profiles. The urban area shoreface presents fine sand sediments, while the other sectors show medium sand. The averaged bathymetric profile shows great proximity to the Urban Area's DoC and morphology. The sediment size used for this last bathymetry was extracted by calculating the median grain size of the entire region at 1.5*$h_{c.}$ The DoC are shown in Fig. 3.

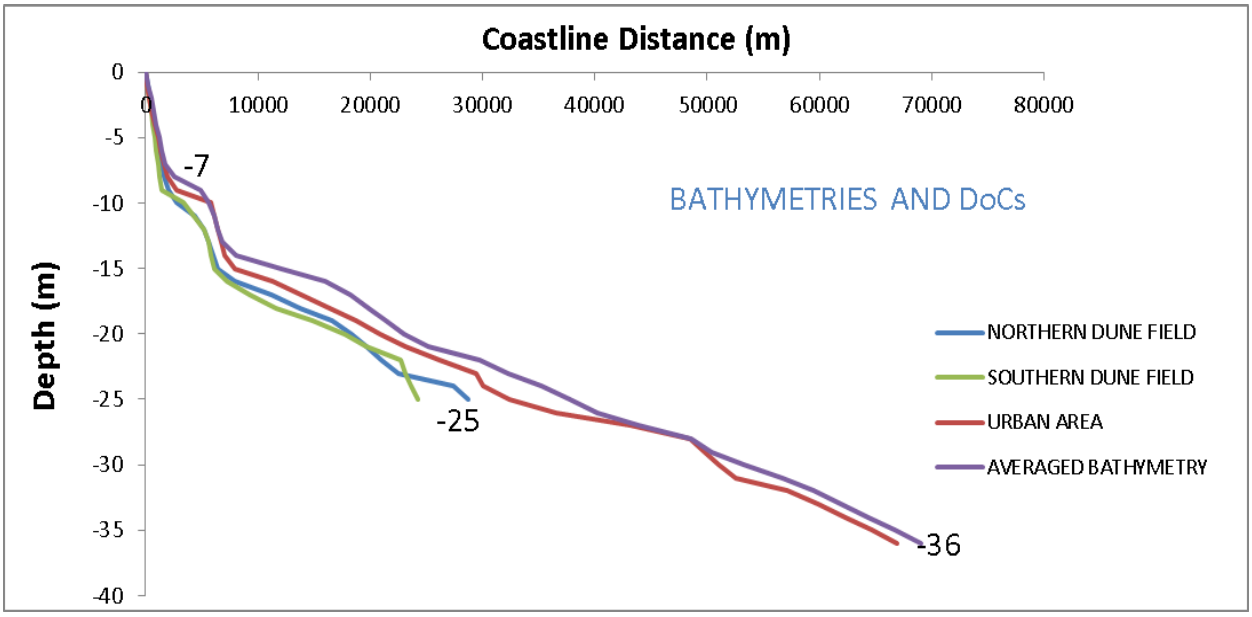

Figure 3. Bathymetries and depths of closure for each site.

2.5 Projected Seal level Rates

Mean regional sea level rates were extracted from Jackson & Jevrejeva (2016), which based their projections on outputs from the Coupled Model Intercomparison Project Phase 5 model and other coupled models. The worst greenhouse gas emission scenario established by the IPCC (AR5, 2014), known as Representative Concentration Pathway (RCP) 8.5, was used. The chosen time horizons for coastline projections were 2040 and 2100. The RanSTM model addresses uncertainty in parameter values by using a probabilistic distribution for sea level rise rates, in which the probability values extracted by Jackson & Jevrejeva (2016) of the 5-95th percentiles were used as the lower bound value, the 50% of occurrence was used as a mean value, and the value from the 95th percentile characterizing the worst possible scenario was used as the upper bound value in the model parametrization. For the 2040 scenario, the obtained sea level rise values were for the lower and modal bounds 0.1 m and for the upper bound 0.18 m. For the 2100 scenario, the lower and modal bounds showed rise of 0.5 m, while the upper bound showed 0.9 m of sea level rise.

2.6 Sedimentary budget estimates

The formulas for the calculation of the sedimentary budget estimates were extracted from Figueiredo (2011). Three values (for the lower, modal, and upper bounds) were obtained for the sedimentary budget in the region, considering the model demands. For defining the lower bound value, calculations were made by using the Dillenburg et al., (2000) long-term simulated erosion rates for the coastal projections of RS (Eq. 4).

For the modal value, the coastline retreat values provided by Albuquerque (2013) for Hermenegildo Beach were used; dune height was extracted from the DTMs generated in this study (Eq. 5).

The sedimentary budget upper boundary value was calculated from stratigraphic data available for Hermenegildo Beach from Dillenburg et al. (2000) and Lima et al. (2013) (Eq. 6).

The formulas used for sedimentary budget estimation are as follows, and listed in Table 1:

$$V = (sediment\ budget\ of\ the\ site's\ coastal\ projection) / (area) \qquad (4)$$

$$V = (C_p * (h_d + h_c)) / years \qquad (5)$$

where,

C_p = coastline recession (m);

h_d = dune height (m);

h_c = upper closure depth (m);

$$\boldsymbol{V = ((B_w + S_w)\ x L_c)\ x\ TRS} \qquad (6)$$

where,

B_w = Barrier Width (m);

S_w = Upper Shoreface Width (m);

L_c = Coastal Cell Length (m);

TRS = Total Regressive Sediment Thickness (m);

Table 1 - Lower, modal, and upper bound sediment budget values for 2040 and 2100.

SEDIMENT BUDGET VALUES ($m^3/m/y$)			
Years	Lower	Modal	Upper
2040	-442	-427	-92
2100	-1577	-1476	-328

2.7 *Simulation design*

2.7.1 Coastline Projections for 2040 and 2100

Initially, three independent simulations were performed. For each simulation, specific geomorphological characteristics (topography and bathymetry) of each site were considered for the development of three different substrates for the urban, northern, and southern areas. Sedimentary budget values and regional sea level rise data were fixed during all simulations according to each time horizon of 2040 and 2100 (Sec. 2.5 and 2.6). For the main result from the simulations, we obtained shoreline projections in each sector using its own topography and bathymetry for 2040 and 2100.

2.7.2 Topographic influence on coastal recession

Three independent simulations were completed to quantify the topographic influence on coastal recession. All of the simulations showed the same previously created averaged bathymetric substrate (Sec. 2.3). The topographic variations consisted of coupling to the averaged bathymetry the southern and northern dune field topographies, as well as, the urban area topography with no urbanization.

The rigid structures in the model input were created by applying a rocky texture where the urbanization occurs along the topographic profile. In contrast, for creation of the urbanized topography without rigid structures, the topographic profile stretch on which the rocky texture was attributed before is substituted with a sandy texture (sand-only profile). This simulation was completed to isolate the bathymetric effects and determine if the major influence in the urban area is provided by the rigid structures or purely by the onshore topography.

2.7.3 *Urban influence on coastal recession*

To quantify the influence of urbanization on the coastline projections, another simulation was performed to compare the urbanized sector without rigid structures (sand-only profile) to the urbanized sector with rigid structures. Therefore, we obtained two distinct substrates with different texture for the site's own bathymetry (different from the averaged bathymetry). Each of these substrates was combined with sedimentary budget and sea level rise rates of the 2040 and 2100 time horizons. From this we obtained projections for each of the substrates, compared them, and quantified the influence of the rigid structures on the coastline recession rates.

2.8 Statistical analysis

A Kolmogorov-Smirnov test for normality was applied to all coastal retreat distribution datasets and all failed, showing that the coastal recession datasets do not show a normal distribution. Therefore, a non-parametric Kruskal-Wallis (K-W) test was performed to determine any statistical significantly differences because of onshore topography and urbanization in the recession rates at a 1% significance. Because it is a two-sample test, simulation results were divided into comparative groups as follows:

For the first set of simulations (Sec. 2.7.1), we performed comparisons coastal recession distribution amongst sites as follows: 1) southern/northern dune fields, 2) southern dune field/urban area, and 3) northern dune field/urban area. To quantify the general significance of onshore topography (only) effects we compared the following (Sec. 2.7.2): 1) southern/northern dune fields, 2) northern dune field/sand-only urban area, and 3) northern dune field/sand-only urban area. Finally, for the last set of simulations (2.7.3) we assessed: structured urban area/sand-only urban area.

3. Results and Discussion

Overall, the results show that the main morphological differences were provided by the structured urban topography and bathymetry, once this profile was differentiated by the presence of rigid structures that cut sediment supply, and a wider and deeper shoreface, which suggested an increased sedimentary demand to achieve its equilibrium (Cowell et al. 1999) when compared to that of the other sites.

Comparisons between coastline recession values are shown as mean recession values (R_{50}) to quantify the influence of each morphologic feature in percentages. The coastline projection maps show the current coastline, mean coastal retreat (at a 50% risk of occurrence), and extreme coastal retreat (at a 1% risk of occurrence).

3.1 Coastline Projections for 2040 and 2100

The 2040 coastline projections (Fig. 4) show that the urban area presented higher recession rates among all the simulations with a mean recession of 159 m (7.57m/year). The southern and northern dune fields showed 77.7 m (3.7 m/year) and 81.3 m (3.87 m/year) of mean coastline recession . The urban area showed 51.4% more retreat than that of the southern sector, and 48.7% more than that of the northern dune field sector, leading to minor recession distances at the last two sites whose difference was less than 10 m (4.42%).

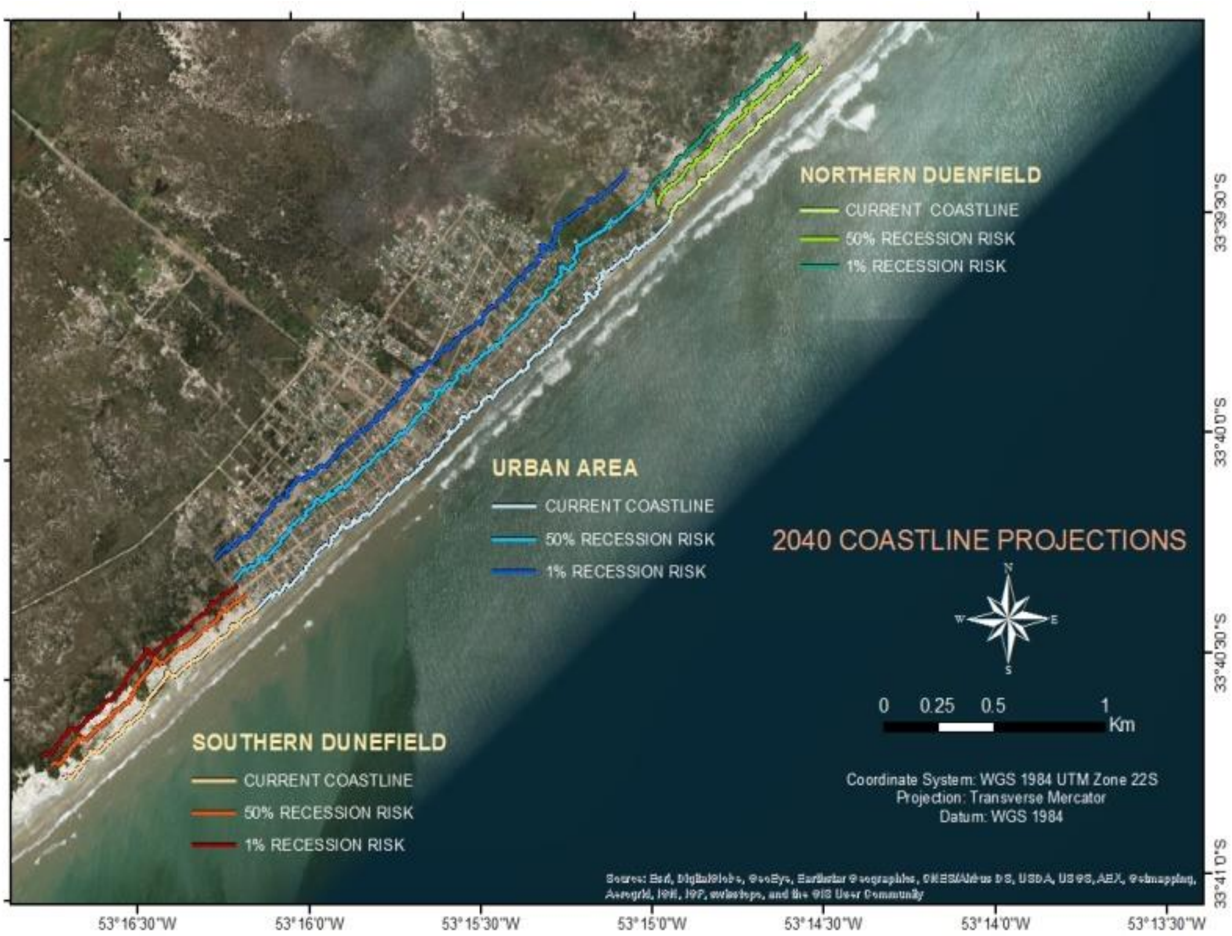

Figure 4. 2040 coastline projections for each site.

For the 2100 projections (Fig. 5), a repetition of the same pattern described for 2040 is evident; that is, the urban area is the most erosive site followed by the northern and southern dune fields, respectively. However, the differences in recession among the sites diminished, as the urban area presented a mean recession of 716 m (8.83 m/year), while the southern and northern dune fields showed 358.2 (4.42 m/year) m and 366.1 m of recession (4.51 m/year), respectively. Therefore, the urban area showed 49.7% and 48.9% more erosion than that of the southern and northern dune fields, respectively, while the difference in the morphology between the dune fields was responsible for only 2.15% of the recession rates. This shows that at longer timescales (2100) either onshore or offshore controls influencing Hermenegildo Beach's coastal behavior diminish, and are masked by sea level rise, that as stated by Figueiredo et al. (2018) will start controlling Hermenegildo Beach's coastline recession when reaching rates of 0.09, 0.12, and 0.16 m. These values are met or even exceeded (Sec. 2.5) by 2040 in this study.

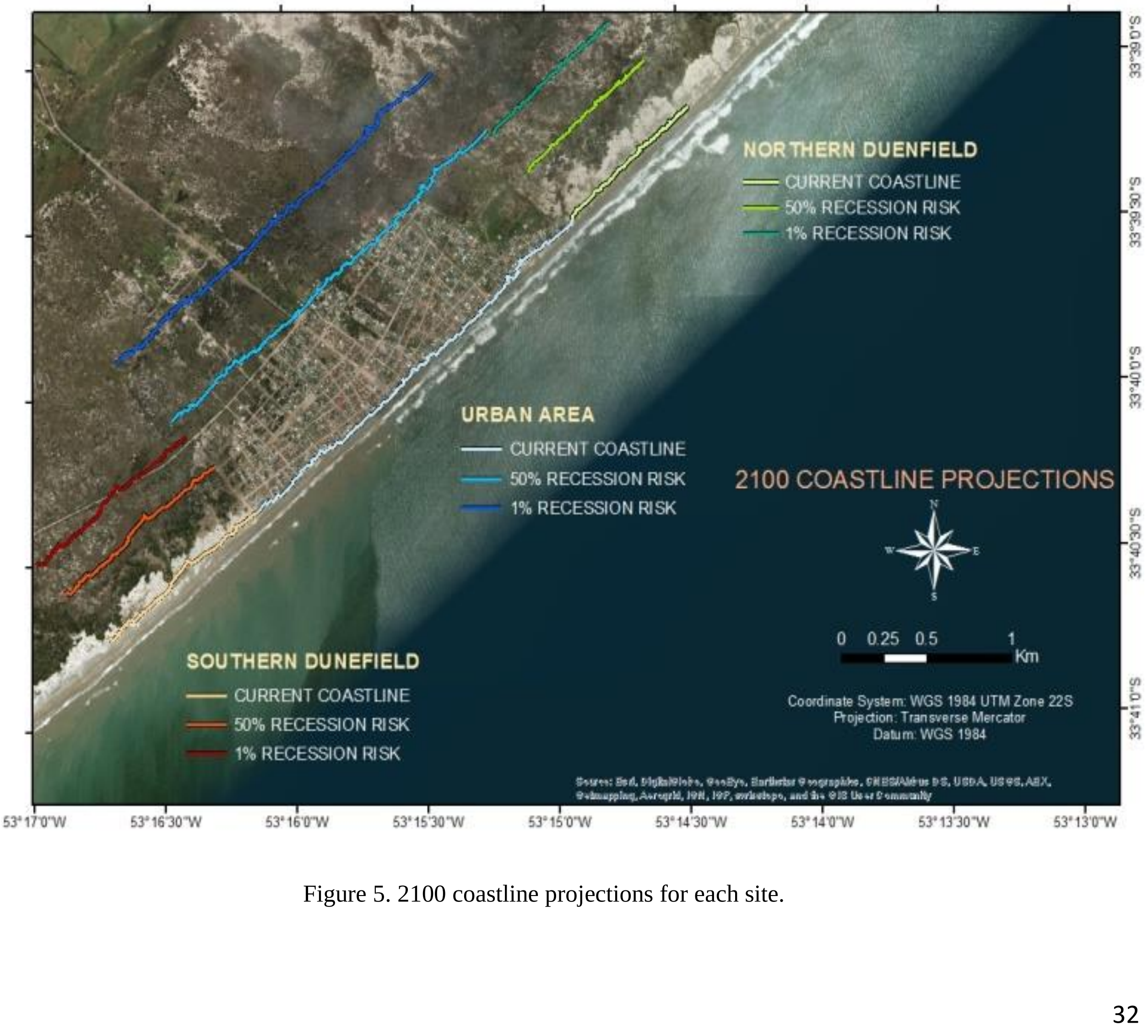

Figure 5. 2100 coastline projections for each site.

We can state that for both time horizons, coastal protection structures do not avoid coastal recession when negative sediment supply and sea level rise work together.

The higher recession distances of the northern dune field, compared to the southern, are expected as the northernmost dune field is slightly more degraded (Maia et al., 2016). This was also confirmed by Albuquerque (2013), although the author presented lower recession rates for the urban area when compared to the dune fields, exposing the implications of applying different methodologies to the same study. These differences are mainly cause of Albuquerque (2013) considered fixed erosional rates for the coastline historical (65 years) trends to project future positions of the coastline, while this study relied on stochastic modelling of different sedimentary budget and sea level change rates, as well as considering shoreface geometrical and textural characteristics and translation.

Figueiredo (2011) also used the RanSTM model to obtain recession distances of 129 m for 2030 projections, though she did not compute the rigid structures in her study. The author shows for 2100 a recession of 521 m, smaller than that presented here (716 m), demonstrating that even when using the same model, local and regional parametrization largely affects results, particularly when simulating long-term coastal behavior (2100).

Not only does the onshore morphology represent differences in sand supply between the dune fields and the urban area, because of the presence of coastal structures but differences in the shoreface extent also occur (Sec. 2.4). As shown by Cowell et al. (1999) and Cowell & Kinsela (2018), the wider the shoreface, the more sediment is needed for filling the accommodation space generated by a rise in sea level, to achieve a dynamical equilibrium state. Therefore, the higher recession values achieved in the urban area are to be expected, once the limited sediment availability driven by the presence of coastal structures may not be sufficient to compensate for the wide shoreface sediment demand.

The sites present low foredunes (< 3 m), easily allowing washover, which according to Cowell et al. (1992) promotes the transgression of the barrier. This, process contributes in the long term to the barrier roll-over, in which the backbarrier is characterized as a sediment sink similar to that which occurs, for example, at Mackarel Beach, Australia (Cowell et al. 1995; Dillenburg et al., 2000). In addition, high recession rates in the presence of urbanization, allows a wider area to be flooded because of paving effects, therefore increasing recession rates. However, the main recession control during sea level rise is provided by shoreface sediment demand rather than barrier roll-over transgression (Kinsela, 2007).

3.2 Topographic influence on coastline recession

Following Experiment 2 (Sec. 2.7.2), we were able to obtain a general quantification of the influence of different onshore topographic variations on coastline recession.

In a comparison among dune fields with the same averaged bathymetry we found that the highest recession distances are provided by the southern dune field with 150.7 m for 2040 and 710.9 m for 2100. We can observe a slight difference comparing the northern and southern dune fields each with their own bathymetry (Exp. 1 Sec. 2.7.1) once the northern dune field sector was the most eroded when compared to the southern. Now, isolating the effects of bathymetric variations between sites (averaged bathymetry) the northern dune field presents recession distances of 148 m for 2040 and 696.9 m for 2100. This inversion is probably because of the bathymetric change, as this result was not expected after field observations of both dunefields described the southern dune field as the most preserved, with higher foredunes and vegetative cover than that of the northern dune field, as occurs in Exp. 1, suggesting that offshore morphology shows relevant differences for these sites. Despite this, the onshore morphological variation between the dune fields with the same averaged bathymetry was responsible only for a 1.79% for 2040 and 1.96 % for 2100 increase in recession distance.

A general comparison, between the northern and southern dune fields and the sand-only urban area (each one with its own topography), was completed by comparing the previous results from this section for the dune fields and coupling the sand-only topography with the same averaged bathymetric profile. For 2040, the sand-only urban area showed 150.4 m of coastal recession and 704.5 m of recession for 2100.

There are not large differences (Fig. 6) in recession rates among sites and the sand-only urban is slightly less eroded than the northern dune field, and slightly more eroded than the southern dune field. These results indicate that the topography at the three sites is nearly the same, with no expressive variations, characterizing a minor difference for the topographic influence on erosion distances. That is in line with the results presented by Kinsela (2007) since only a high volumetric difference is capable of significantly affecting coastline recession values (25% of volume reduction for 5 to 10% recession distances).

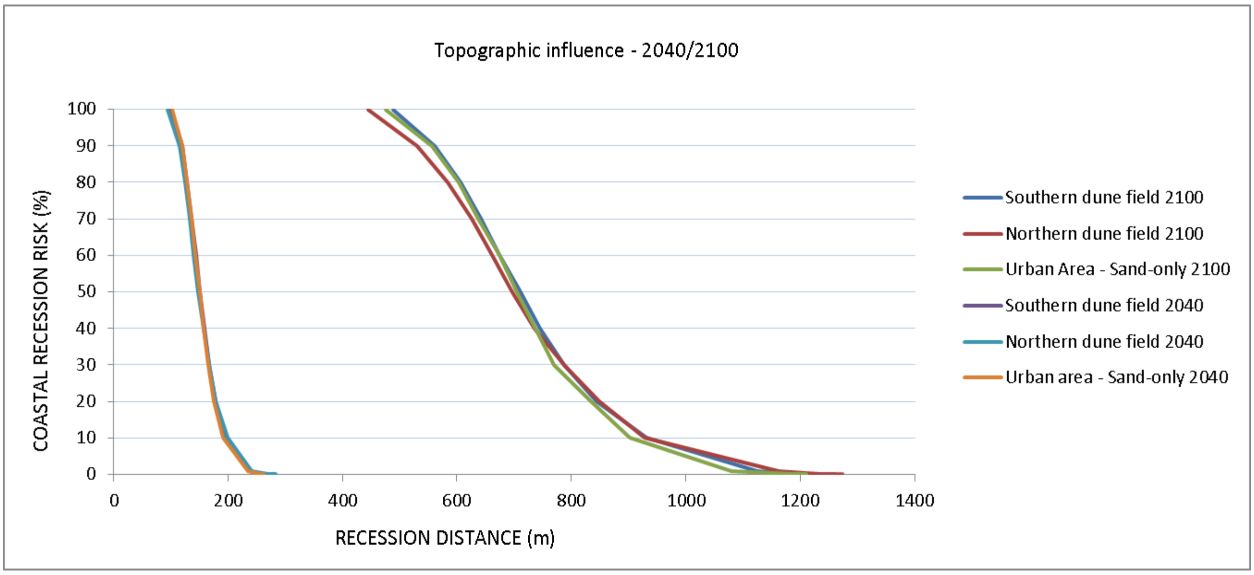

Figure 6. Recession distances for the dune fields and structured urban area with an averaged bathymetry.

3.3 Urban influence on coastline recession

To quantify the influence of a structured onshore on the coastal response under rising sea levels, two simulation experiments were performed for the urban area varying its onshore topography but maintaining its own bathymetry (Exp. 3 Sec 2.7.3). One topography represented the urban area with rigid structures and paving (real situation), and the other a sand-only profile substrate. In terms of mean recession distances (Fig. 7), the former presented 159 m, while the last 137.5 m of mean costal retreat for 2040, therefore a 13.52% increase in recession distance is due to the presence of structures and paving in the onshore.

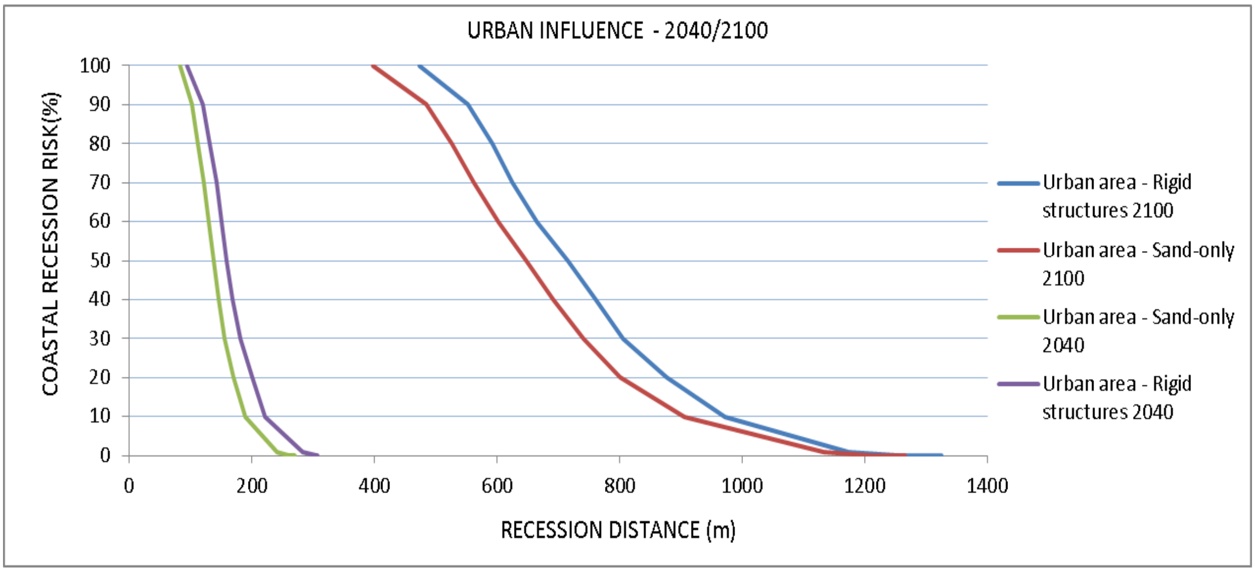

Figure 7. Recession distances for the urban area with associated risk of exceedance by 2040 and 2100. Structured urban area (blue and purple lines), sand-only profile (red and green lines).

For increased sea level rates, for 2100 projections, we observe a mean coastline recession distance of 716 m at the structured urban area, and 647.3 m for the sand-only profile, characterizing an increase of 9.59% in recession rates because of the urbanization. Similar findings were obtained by Cowell et al. (2006) who compared a structured profile to the same sand-only profile at Manly Beach in SW Australia. Their results showed that the structured profile (sea-wall and pavement) was responsible for a 20% increase in the recession rates, and the influence was sufficiently strong to mask the natural protection offered by a reef offshore.

The limited sediment availability provided by the suppression of the dunefields imposed a similar behavior to the findings of Adlam (2008), who showed increased recession distances reaching 77.7 m for 2100, in a deltaic beach at Lido di Ostia, Italy, once the sediment supply from the Tiber River was interrupted because of dam construction. Although not presenting the same RCP scenario, our study resulted in increased mean recession distances for 2100 (716 m), which are one order of magnitude greater than Adlam`s, when accounting for a urbanized dune field. We can assume that these differences are provided not only by the local scarcity of alongshore and cross-shore sediment supply but also because of the paving on top of the foredunes that increases coastal recession and flooding processes over Hermenegildo Beach low-lying area. We can confirm that the presence of urbanization increases coastal recession rates when compared to a sand-only profile.

3.4 Statistical Analysis

In the comparisons among the exp. 1 results, the K-W test indicate that all recession distance distributions (Table 2) are significantly ($P<0.001$) different, pointing out that morphological differences among sites generate differences in coastline recession. An exception occurred for the 2100 comparison between the northern and southern dune fields. This shows that the difference in dune morphology or bathymetric influence on coastline retreat is obscured by the increased sea level rise rates; therefore, the influence is weakened. Our findings agree with those of Roy et al. (1994) who stated that under rapid sea level change substrate site morphology is more influential in coastline recession rates than local sediment budget, which is clearly shown by the differences in recession rates between the urban area and the other studied sites (the southern and northern dune fields).

Table 2 - Statistical comparisons between recession distance distributions. Northern dune field (ND) southern dune field (SD), urban structured (US) and sand-only (USO).

Exp. 1 - Statistical comparisons between recession distance distributions –

own topography and bathymetry tests		
Time horizon	Sites	P-value
2040	SD/ND	$4.052*10^{-5}$
	SD/US	$2.057*10^{-315}$
	ND/US	$7.479*10^{-305}$
2100	SD/ND	0.066
	SD/US	$1.647*10^{-316}$
	ND/US	$2.035*10^{-303}$
Exp. 2 - Statistical comparisons for quantification of topography effects		
2040	SD/USO	0.482
	ND/USO	0.381
	ND/SD	0.126
2100	SD/USO	0.195
	ND/USO	0.452
	ND/SD	0.045
Exp. 3 - Statistical comparisons for quantification of urbanization effects		
2040	US/USO	$3.342*10^{-44}$
2100	US/USO	$1.106*10^{-20}$

Nonetheless, we noticed that the urban area topo-bathymetric influence is sufficiently strong to not be exceeded by sea level control in both time horizons.

For comparisons among sites with their own topography and averaged bathymetry (Exp. 2), we noticed that there are no significant differences among the dune fields and sand-only urban area recession distances (2040-2100). The dune fields' morphology is not sufficiently different to influence coastline recession. When compared to the previous experiment we can say that for 2040 the shoreface characterization was the primary contributor to coastline retreat, while for 2100 neither the onshore nor the offshore profiles could overcome the influence of sea level rise rates on coastline retreat.

A comparison between the structured urban area and the sand-only profile (Exp. 3) showed that this site is significantly affected by changes in sediment availability and substrate texture and geometry for both time horizons (2040/2100), allowing to conclude that rigid structures significantly influence coastal recession rates.

3.5 Conclusions and suggestions

The main conclusion of this study is that the presence of rigid structures significantly affects coastline recession, more than any other onshore morphological influence that occurs in a way that even when sea level rise rates are increased (2100), its effects are still significant.

Differences between the southern and northern dune fields and the sand-only urban profile are negligible and not sufficient to influence on coastal recession distances significantly.

Shoreface influence quantification was beyond the scope of this study, but we can certainly encourage further investigations to be done in that direction, since there was some indication that it contributes to coastal retreat in the site, mostly in the presence of a wider shoreface associated with urbanization.

The current study provided a quantitative assessment of some the factors that influence coastal response under sea level rise scenarios. In special to the question that urbanization on the top of foredunes significantly increases coastal recession. As widely suggested we agree that it is crucial that set back lines are put in place in future human settlements developed at Hermenegildo area, and at any other coastal cities around the world. The presence of urbanization along the active beach constitutes a risk for population and infrastructure who is subjected to erosion and flooding events. Therefore the results provided by this study may give the basis for managers to prevent the construction of coastal cities at an area under risk (either high or low).

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CAPÍTULO III

1. Considerações Finais e Aplicações do Estudo

A zona costeira é extremamente susceptível as mudanças climáticas alterando sua morfologia conforme os processos erosivos costeiros se intensificam no cenário global de mudanças climáticas. O aumento do nível do mar e o consequente incremento dos efeitos erosivos em um local como o Balneário Hermenegildo, que apresenta naturalmente uma forte tendência retrogradacional, é ainda mais agravado em decorrência da influência antrópica no local.

O seguinte trabalho permitiu quantificar a influência da urbanização no recuo da linha de costa, bem como a influência de diferentes topografias ao longo da área de estudo. A partir dessa investigação pode-se concluir que a urbanização influencia significativamente nas taxas de recuo da linha de costa em cenários de elevação do nível do mar, e balanço sedimentar negativo, constituindo-se como fator preponderante nas distancias de recuo da mesma. A antropização do campo de dunas frontais do balneário e a construção de estruturas de proteção costeira permitiu a ocorrência de um déficit sedimentar no local, a impermeabilização do solo, e por consequência o aumento do recuo da LC nesse setor, pela constante erosão, e inundação devido à pavimentação do local.

Pode-se afirmar que as estruturas de contenção e a pavimentação da área urbanizada agravam os efeitos erosivos, acelerando o recuo da linha de costa, ao contrario dos setores naturais dos campos de dunas cujas diferenças morfológicas apresentam-se insignificantes nas variações da mesma.

O estudo do comportamento e influência da antepraia está além do escopo do trabalho, porém há evidência de que a antepraia possa significativamente afetar o recuo linha de costa, sendo sugerida uma investigação nesse sentido para a área.

Através desse trabalho espera-se subsidiar o futuro gerenciamento costeiro do local que historicamente sofre com os efeitos erosivos do mar. Espera-se, também dar visibilidade aos impactos trazidos pelo homem através da má utilização e gestão das regiões costeiras, que acarretam em sérios danos e riscos as populações litorâneas.