



**UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS**

**MORFODINÂMICA DE ESPORÕES ARENOSOS
LAGUNARES CUSPIDADOS, LAGOA DOS PATOS, BRASIL**

INAIÊ MALHEIROS MIRANDA

**ORIENTADOR: Prof. Dr. Elírio Ernestino Toldo Júnior
CO-ORIENTADOR: Prof. Dr. Antonio Henrique da Fontoura Klein**

Porto Alegre, 2020.

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***Aos meus pais, Angelita e Hadilson,
com amor.***

*“Escolheremos o nosso próximo mundo através daquilo que aprendermos neste.
Não aprender nada significa que o próximo mundo será igual a este, com as
mesmas limitações e pesos de chumbo a vencer”*

-Richard Bach-

*“Tenha a coragem de seguir o que o seu coração e a sua intuição dizem,
de alguma maneira eles já sabem o que você realmente quer se
tornar. Tudo o mais é secundário”*

-Steve Jobs-

*“Há homens e mulheres que lutam um dia e que são bons.
Há outros(as) que lutam um ano e são melhores.
Há os que lutam muitos anos e são muito bons.
Mas há os que lutam toda a vida e estes são imprescindíveis”*

-Bertolt Brecht-

*“Só o imperfeito evolui, o perfeito já se estagnou, cristalizou-se. Só o
imperfeito tem futuro.”*

-Bert Hellinger-

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RESUMO

A presente pesquisa de Tese destinou-se a contribuir para o aumento no entendimento da morfodinâmica de esporões arenosos cuspidados nas margens de sistemas lagunares, tendo como área de investigação o extenso sistema lagunar (>10.000 m²) da Lagoa dos Patos (BR), isto é, elucidar a interação entre os processos hidrodinâmicos, sedimentares e a morfologia desse sistema costeiro altamente complexo em escala de evento à escala histórica. O objetivo central consistiu na análise do suprimento sedimentar para os esporões e na descrição e quantificação dos processos morfodinâmicos e hidrodinâmicos (especificamente as ondas de gravidade) que regem o comportamento costeiro da linha de costa lagunar e dos depósitos de esporões arenosos rítmicos presentes na margem lagunar central oeste da laguna, em escala de evento à escala histórica. A metodologia empregada consistiu em duas etapas: 1. a utilização de técnicas de geoprocessamento para a extração da posição da linha de costa lagunar por meio da base de dados de imagens dos satélites LandSAT 5TM e 8^{OLI}, a fim de avaliar se os arcos praiiais (áreas fontes de sedimentos para o crescimento dos esporões por meio da erosão e subsequente deriva litorânea) apresentaram representativa retração da posição da linha de costa entre os anos de 1984 e 2013; 2. o emprego do pacote de modelos Delft 3D para a modelagem computacional dos processos hidrodinâmicos (ondas e correntes induzidas por ondas) e do transporte de sedimentos ao longo das margens lagunares. O modelo foi configurado e validado com dados medidos *in situ* pelo ondógrafo direcional *Warider Datawell Mark III*, permitindo sua aplicação para a simulação de representativos casos de ondas geradas por vento no interior da Lagoa dos Patos. A análise das mudanças costeiras em escala histórica (1984-2013) demonstrou que a linha de costa dos arcos praiiais apresentou um comportamento predominantemente estável, com 60% do trecho costeiro do arco praiial norte (Arambaré) e 74% do trecho costeiro do arco praiial sul com valores estáveis, e uma taxa média anual geral dentro do valor de incerteza (± 1.05 m/ano), o que se constitui na primeira evidência da redução significativa no suprimento sedimentar para o contínuo crescimento lateral dos esporões. Os resultados da modelagem numérica demonstraram que os esporões arenosos são responsáveis por representativas alterações no clima de ondas lagunar em função: 1. do processo de atenuação de ondas pelos esporões, 2. da formação de zonas de sombra (ou no estabelecimento de sub-áreas de geração de ondas locais) e; 3. da refração de ondas sobre os esporões. Enfatiza-se, também, a existência de padrões regionais na distribuição espacial das características das ondas incidentes ao longo das margens lagunares (especificamente a distribuição longitudinal da energia [W/m] e dos ângulos de incidência de ondas com relação à orientação geral da linha de costa [$\varphi-\theta$]), cuja configuração demonstra a tendência à diminuição do poder erosivo dos processos ondulatórios dos campos de ondas que se propagam ao longo do eixo lagunar principal (longitudinal), os quais são normalmente assumidos como os principais agentes das mudanças morfológicas nas margens de lagunas alongadas. Destacadamente, há uma baixa ocorrência de ondas incidentes com ângulos oblíquos ($30^\circ < \varphi-\theta > 60^\circ$ – menos de 19%), considerando todos os campos de ondas analisados (NNE, NE, ENE, E, ESE, SSE, S-SSW, SW). Isso é atribuído à influência dos esporões arenosos no clima de ondas lagunar e ao estágio avançado de desenvolvimento da linha de costa. Com relação à dinâmica sedimentar, a deriva litorânea se processa nos dois sentidos, com transporte sedimentar líquido para sul, concordante com a direção de crescimento dos esporões arenosos na margem oeste. Entretanto, a análise do balanço sedimentar identificou um padrão de áreas inter-relacionadas, fontes e receptoras de sedimentos ao longo dos arcos praiiais. Nos quais, os segmentos costeiros no centro dos arcos praiiais atuam como áreas de armazenamento temporário de sedimentos, enquanto as células litorâneas no setor sul constituem-se na principal área fonte de sedimentos para os esporões submersos. Foi demonstrada, também, a importante influência que fatores controladores locais, como a exposição costeira e a morfologia do prisma praiial submerso, exercem na deriva litorânea nos arcos praiiais, e por sua vez, no controle do suprimento de sedimentos para os esporões. Por fim, constatou-se que os esporões estão em uma fase de crescimento limitada, em que se observa um elevado coajuste mútuo entre a morfologia e a hidrodinâmica, e a consequente carência no suprimento sedimentar para os depósitos de esporões arenosos submersos, conforme evidenciado pela ausência de taxas representativas de retração da linha de costa em escala histórica e pela reduzida taxa de aporte sedimentar para os esporões – 2.900 m³/ano para o esporão Dona Maria e 900 m³/ano para o esporão do Vitoriano (considerando a magnitude das feições) –, resultando, portanto, na sua erosão natural.

Palavras-chave: Sistemas Lagunares, Esporões Cuspidados; Dinâmica de Ondas, Deriva Litorânea, Balanço de Sedimentos.

ABSTRACT

This thesis intended to contribute to the knowledge of cusped spits morphodynamics into lagoon coastlines, having as a study area the extensive ($>10,000 \text{ m}^2$) lagoon system of Lagoa dos Patos (Brazil). This is, elucidate the interaction between the hydrodynamic and sedimentary processes and the morphology of this highly complex coastal system in an event to a historic scale. It had as main aim the analysis of the sediment supply to the spits and the description and quantification of the morphodynamic and hydrodynamic processes on the lagoon cusped coast, in an event- to historical scale. The methodology consisted of two stages: 1. the use of geoprocessing techniques to extract the shoreline position of the rhythmic coast from the database of the LandSAT 5TM and 8^{OLI} satellite images, to investigate if the bay beaches presented representative shoreline retreat rates from 1984 to 2013, as it is assumed that the erosion of the updrift beaches are the main sources of sediments to the spits and, 2. the modeling of the hydrodynamic (wind-waves and wave-induced currents) and sedimentary processes by using the suite Delft 3D. The model was configured and validated against measured wave data by the Waverider Datawell Mark III and used to simulate the lagoon wave fields forced by representative wind cases. The results showed that in a historic scale (decades) the coastline presented a prevailing stability trend, with 60 % of the northern bay beach (Arambaré) and 74 % of the southern bay beach with stable values, and a general average change rate inside the uncertainty error ($\pm 1.05 \text{ m y}^{-1}$), which demonstrates that the sediment supply to the continuous growth of the spits has been significantly reduced on the analyzed three decades. The model results demonstrated that the emerged and submerged spits has a significant influence on the lagoon wave fields through: 1. the wave attenuation process; 2. the formation of wave shadow zones (or subareas of local wave generation); and 3. refraction. It is also highlighted the occurrence of regional patterns on the alongshore distribution of the incident wave characteristics along the lagoon cusped coast (specifically the energy [W/m] and the incident wave angles to the shore [$\varphi-\theta$]), whose configuration tends to decrease the erosive power of the wave fields propagating across the long lagoon axis, which are normally assumed to be the main drivers of morphological changes on elongated lagoons. Another important fact to highlight is the low occurrence of oblique local wave angles to the shore ($30^\circ < \varphi-\theta < 60^\circ$ - less than 19%), considering different directions of wave fields (NNE, NE, ENE, E, ESE, SSE, S-SSW, SW). This is attributed to the cusped spits influence on the lagoon wave field and the advanced stage of this coastline. In regards to the resultant nearshore sedimentary dynamic, the longshore drift has a bidirectional pattern with net transport to the south, in accordance with the growth direction of the spits on the west lagoon coast. However, the sediment budget analysis revealed a pattern of inter-related sources and temporary storage areas along the bay beaches. In which, the coastal segments in the center of the bay beaches act as temporary storage areas, while the southern coastal segments are the main sources of sediments to the submerged spits. It was also demonstrated that local conditioning factors, such as coastline exposure and the shoreface morphology, affect the longshore transport within the bays, which controls the amounts of sediments supplied to the spits. Ultimately, it was found that the cusped spits are in a phase of limited growth, in which it is observed a high mutual co-adjustment between the morphology and the incident wave field, and the consequent starvation on the sediment supply to the submerged spits (also referred to as subaqueous bars), as evidenced by the absence of representative shoreline retreat rates in a historic scale, and by the reduced rate of sediment input to the spits, $2,900 \text{ m}^3 \text{ y}^{-1}$ to Dona Maria spit and $900 \text{ m}^3 \text{ y}^{-1}$ to Vitoriano spit (taking into consideration the magnitude of the features), therefore, resulting in its natural erosion.

Key-words: Lagoon Systems; Cusped spits; Wave Dynamic, Longshore Drift; Sediment Budget.

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SOBRE A ESTRUTURA DESTA TESE

Este documento está estruturado em formato de artigos, conforme estabelecido na Norma 103 – Submissão de Teses e Dissertações, de acordo com o Regimento do Programa de Pós-graduação em Geociências (PPGGEO/IG/UFRGS). Está, portanto, subdividida da seguinte maneira:

- **Capítulo 1) Introdução:** apresenta a introdução ao tema abordado na Tese, contextualização da área de estudo, justificativa, premissas, hipótese e a descrição dos objetivos da pesquisa de Doutorado;
- **Capítulo 2)** Consta o estado da arte sobre o tema de pesquisa: **Morfodinâmica de Esporões Arenosos Cuspidados nas Margens de Sistemas Lagunares;**
- **Capítulo 3)** Artigo publicado na revista *Journal of Coastal Research*:
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- **Capítulo 6)** Considerações Finais;
- **Apêndices.**

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CAPÍTULO 1. INTRODUÇÃO

Nos ambientes de águas continentais de grandes espelhos d'água (ex.: lagos, lagoas, reservatórios e estuários), o vento constitui-se na principal forçante da geração dos fenômenos de circulação e perturbação da superfície livre (MARQUES, 2013). O tamanho das ondas “*sea waves*” geradas no interior de corpos hídricos é controlado pela área da pista de atuação do vento “*fetch*” e pela batimetria subjacente. Assim, quanto maiores o comprimento e a largura da pista de vento, maior a quantidade de energia transferida pelo vento para a massa d'água, maior a amplitude das ondas geradas localmente e maior o potencial de energia a ser despendido com a sua rebentação na costa.

As ondas constituem-se nas principais agentes modeladoras dos esporões arenosos nas margens de sistemas lagunares. E, assim como em outros ambientes costeiros compostos por sedimentos inconsolidados e com pista de vento restrita “*fetch-limited environment*”, a condição de equilíbrio é alcançada quando a energia de onda é eficientemente dissipada ao longo da costa. Deste modo, muitas margens lagunares apresentam uma configuração oval, com o eixo principal coincidindo com a direção dos ventos predominantes (Figura 1a); alternativamente, lagos, lagoas e lagoas mais alongados adquirem um formato com extensas baías divididas por esporões arenosos pareados (Figura 1b) e, mesmo que as margens do corpo hídrico não sejam favoráveis à reorganização morfológica (ex.: costas rochosas), frequentemente encontram-se sinais parciais de equilíbrio de ajuste da forma da linha de costa em planta (Figura 1c) (CARTER, 1988).

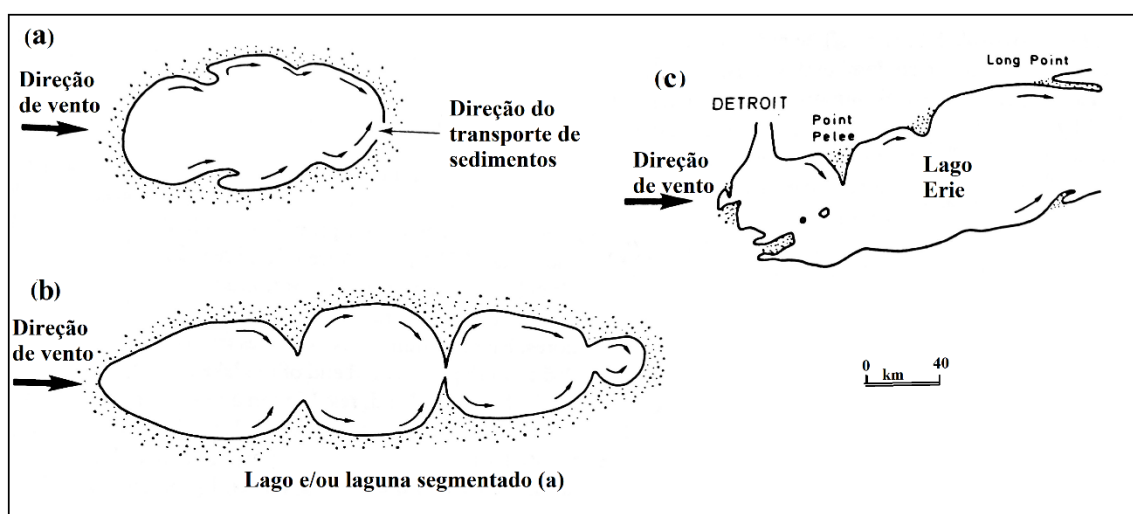


Figura 1. Esquema ilustrativo de costas de lagos e lagoas com relação à direção de vento e ao desenvolvimento de formas da linha de costa em planta. Figura 1a) Eixo principal de um corpo lagunar coincidente com a direção de ventos predominantes e a direção preferencial do transporte de sedimentos; Figura 1b) Desenvolvimento de extensas baías segmentadas por esporões pareados em corpos lagunares mais alongados; Figura 1c) Sinais parciais

de equilíbrio de ajuste da forma da linha de costa em planta em margens lagunares não favoráveis à reorganização morfológica.

Fonte: modificado de Carter (1988).

Os esporões abrigam uma complexidade de processos e respostas costeiras que operam em diversas escalas temporais e espaciais (GILBERT, 1890 *apud* ORFORD, 2004; DAVIES 1896 *apud* ORFORD, 2004; EVANS, 1942; ZENKOVITCH, 1959; CARTER, 1988; ASHTON; MURRAY; ARNAULT, 2001; ASHTON; MURRAY, 2006a, 2006b; RANDAZZO, JACKSON; COOPER, 2015), estando inseridos entre as feições geomorfológicas mais dinâmicas da superfície terrestre e apresentando elevada resposta adaptativa às variações nas taxas de suprimento e na dispersão sedimentar (RANDAZZO; JACKSON; COOPER, 2015). Constituem-se, portanto, em uma excelente oportunidade para o estudo dos processos morfodinâmicos dominantes em ambientes costeiros nas diferentes escalas temporais.

A Lagoa dos Patos abriga em seu interior extensas praias lagunares com formato arqueado (arcos praias) e depósitos de esporões arenosos em formato de cúspide. Seu extenso espelho d'água “*fetch*”, com comprimento e larguras aproximados de 220 km e 32-61 km, respectivamente, possibilita a geração de ondas de representativa energia. Isto é evidenciado no trabalho de Toldo, Almeida e Corrêa (2003), os quais, a partir do emprego da metodologia utilizada pelo *U. S. Army Coastal Engineering Research Center* (1977), encontraram máxima altura de onda significativa (H_s) de 1,6 m e período de pico (T_p) de 4,8 s, com uma condição de vento de 28 m/s de velocidade e direção WNW após 1 hora e 30 minutos sob uma pista de vento “*fetch*” de 35 km de comprimento. Além disso, a elevada hidrodinâmica desse sistema lagunar também é evidenciada pela ausência de colonização de vegetações sobre os esporões submersos, ao passo que juncais podem ser encontrados ao longo de porções abrigadas da linha de costa.

As modificações (transformações) sofridas pelas ondas ao se propagarem de águas profundas para águas rasas e interagirem com a morfologia submersa, determina o modo como essa agente modeladora da evolução costeira será atenuada ao longo da costa, o que implica na sua efetividade no processo erosivo, na determinação de áreas propensas à erosão, e nas mudanças contínuas e cumulativas do sistema costeiro em análise. E a modelagem numérica constitui-se em uma ferramenta essencial na predição de tais processos, pois é um método de pesquisa que fornece aos engenheiros costeiros e cientistas uma ampla visão do conjunto de processos que ocorrem na zona costeira, faixa relativamente estreita na qual situa-se a maioria das atividades humanas, e na qual representativos volumes de sedimentos são transportados,

erodidos e depositados, ocasionando as mudanças morfológicas no ambiente costeiro, concomitantemente com o representativo transporte de nutrientes e poluentes (ROELVINK; RENIERS, 2012).

Neste sentido, a presente pesquisa de Tese destina-se a contribuir para o melhor entendimento da morfodinâmica de esporões arenosos rítmicos nas margens de sistemas lagunares. Para tanto, foram utilizadas técnicas de geoprocessamento para o monitoramento da mobilidade da linha de costa, e foi empregado o pacote de modelos Delft 3D para a modelagem numérica de ondas e do transporte de sedimentos no interior da Lagoa dos Patos (RS, Brasil), o que permitiu uma compreensão, de modo abrangente, da dinâmica atual do sistema costeiro em análise. No primeiro artigo (capítulo 3), a evolução da linha de costa é analisada em diferentes escalas temporais, de evento (anos) à escala histórica (décadas, 1984-2013), para investigar se há possíveis tendências erosivas ao longo dos arcos praias, principal fonte de sedimentos para os esporões. No segundo artigo (capítulo 4), é avaliado o controle que a configuração da linha de costa cuspidada e sua associada morfologia submersa (em particular os extensos depósitos de esporões submersos) exercem no clima de ondas da laguna, por meio da análise da atenuação de onda e da redistribuição das propriedades dos campos de ondas incidentes nas praias lagunares – especificamente a energia (W/m) e o ângulo de incidência (φ° - θ°) de onda. No terceiro artigo (capítulo 5), são acessados os principais padrões na deriva litorânea dos sedimentos, considerando casos extremos e médios de campos de ondas representativos, complementado pela proposição de um modelo de balanço regional de sedimentos para a linha de costa cuspidada em questão.

1.1. JUSTIFICATIVA / PROBLEMÁTICA

As mudanças morfológicas e a associada evolução costeira induzida por causas naturais ou pela ação humana podem apresentar grande variabilidade nas mais diversas escalas temporais e espaciais (STIVE *et al.*, 2002), assim como a nossa capacidade de compreender e principalmente prever tais mudanças ainda se encontra limitada, o que dificulta no processo de tomada de decisão com vistas a garantir a adequada gestão dos recursos naturais e a resiliência das comunidades costeiras. Neste sentido, pesquisadores e gestores costeiros têm demonstrado um crescente interesse na predição do comportamento da linha de costa em largas escalas temporais e espaciais (ELLS; MURRAY, 2012; NICHOLLS *et al.*, 2013). Contudo, ainda há uma demanda para a melhora na capacidade preditiva das mudanças que ocorrem localmente (FRENCH *et al.*, 2016) para melhor informar ao planejamento costeiro.

A importância do estudo dos esporões arenosos nas margens do sistema lagunar da Lagoa dos Patos reside nos fatos de os mesmos; 1. tratarem-se da principal feição morfológica da laguna, constituindo-se em um importante registro geológico dos processos sedimentares no tempo e no espaço (TOLDO, 1991); 2. controlarem o balanço de sedimentos da costa, constituindo-se em importante estoque de sedimentos e; 3. fornecerem proteção natural para a linha de costa lagunar.

Neste contexto, a presente Tese de Doutorado busca aprofundar o conhecimento científico a respeito dos processos morfodinâmicos que regem as mudanças na morfologia submersa e no comportamento de linhas de costas cuspidadas “*cuspedate shorelines*”, assim como complementar a base de informação dos processos hidrodinâmicos e sedimentares ao longo da margem central oeste da Lagoa dos Patos em escala de evento à escala histórica. Realiza-se, assim, incremento a extensa pesquisa científica realizada por Toldo (1989, 1991, 1994), Toldo, Almeida e Corrêa (2003) e Toldo *et al.* (2006a) ao longo de toda a linha de costa do extenso sistema lagunar (> 10.000 km² de área) da Lagoa dos Patos.

1.1.1. Perguntas norteadoras da pesquisa

- 1) Os esporões arenosos ainda estão recebendo suprimento sedimentar significativo proveniente da erosão dos arcos praias?
- 2) De que maneira os esporões arenosos influenciam nos campos de ondas no interior da Lagoa dos Patos e, por consequência, nos modos de incidência de ondas ao longo dos arcos praias adjacentes?
- 3) Os esporões arenosos contribuem para a atenuação da energia de onda dentro do corpo lagunar? Em que grau?
- 4) Quais são os principais padrões no transporte longitudinal de sedimentos para cenários extremos e médios de campos de ondas geradas pelo vento local de diferentes direções?
- 5) Quais são as principais tendências erosivas e deposicionais ao longo dos arcos praias e esporões arenosos?
- 6) O sistema praias analisado atingiu um estágio de equilíbrio/ estabilidade?

1.2. PREMISSAS

Esta pesquisa de Tese está pautada na bem estabelecida premissa de que os esporões crescem a partir da deriva litorânea (BRUNN, 1954 *apud* ASHTON *et al.*, 2007). Entende-se, portanto, que o seu processo de formação e desenvolvimento está intrinsecamente relacionado com a disponibilidade e/ou o suprimento de sedimentos transportados por correntes longitudinais, a partir de um setor costeiro a montante “*updrift*” do esporão até a sua terminação (ZENKOVITCH, 1959; ROSEN, 1975; TOLDO, 1989, 19991, 1994; HÉQUETTE; RUZ, 1991; ASHTON; MURRAY; ARNAULT, 2001; ORFORD, 2004; ASHTON; MURRAY, 2006a, 2006b; PETERSEN; DEIGAARD; FREDSOE, 2008; ASHTON *et al.*, 2009, 2016; KUMAR; NARAYANA; JAYAPPA, 2010; KUMAR; DEEPIKA; JAYAPPA, 2013; UDA; SERIZAWA; MIYAHARA, 2014).

Os esporões cuspidados, em específico, tratam-se de estruturas emergentes da auto-organização da linha de costa, os quais têm seu processo de formação e evolução fundamentado na existência de uma instabilidade costeira, ocasionada pela elevada proporção de frentes de ondas incidentes (φ°) com elevada obliquidade com relação à orientação geral da linha de costa (θ°) (ZENKOVITCH, 1959; ROSEN, 1975; ASHTON; MURRAY; ARNAULT, 2001). Este ângulo crítico ($\varphi^\circ - \theta^\circ \sim 45^\circ$) é responsável pela maximização na deriva litorânea sedimentar (DE-LANBLARDIE 1789 *apud* ZENKOVITCH, 1959; KOMAR, 1971) (Figura 2). E por consequência, acarreta em elevados gradientes no transporte sedimentar longitudinal, resultando em intensos processos erosivos e deposicionais, que podem dar origem a feições costeiras de larga-escala em forma de cúspide “V”, dependendo da proporção de ondas incidentes com elevada obliquidade ($\varphi^\circ - \theta^\circ$) (ZENKOVITCH, 1959; ROSEN, 1975; COOPER, 1994; ASHTON; MURRAY; ARNAULT, 2001; ASHTON; MURRAY, 2006a, 2006b).

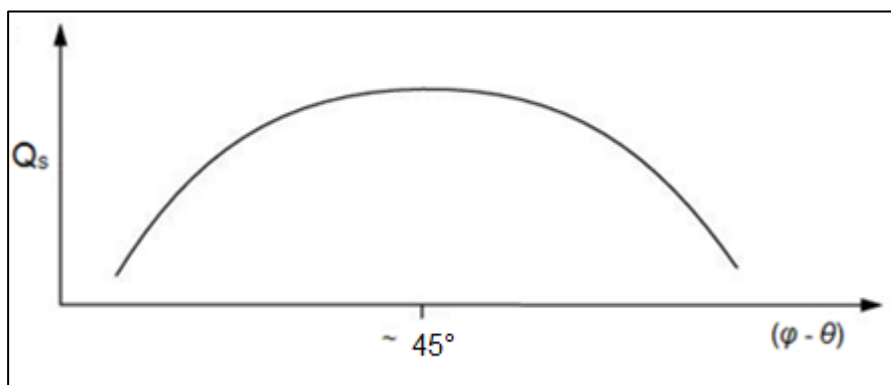


Figura 2. Gráfico ilustrativo demonstrando a relação entre a obliquidade do ângulo de incidência de onda com respeito à costa ($\varphi^\circ - \theta^\circ$) e a maximização e o decaimento no transporte longitudinal de sedimentos. O transporte longitudinal de sedimentos (Q_s) na zona de arrebatção é nulo, ou praticamente nulo, para ondas com incidência normal ($\varphi^\circ - \theta^\circ = 0^\circ$) e transversal ($\varphi^\circ - \theta^\circ = 90^\circ$) à linha de costa, possuindo um valor máximo com o ângulo de incidência de onda em torno de 45° (KOMAR, 1971).

Fonte: modificado de Ashton, Murray e Arnault (2001).

Assume-se, também, que os processos longitudinais imperam sobre os processos transversais na evolução da linha de costa, especialmente para o caso de linhas de costa com elevada sinuosidade (ASHTON; MURRAY; ARNAULT, 2001; LOPEZ-RUIZ, 2014), como é o caso da costa rítmica “*cusate shoreline*” da margem central oeste da Lagoa dos Patos.

1.3. HIPÓTESE

Em concordância com as premissas preestabelecidas, a hipótese levantada nesta tese argumenta que os esporões arenosos localizados no setor central da margem oeste da Lagoa dos Patos atingiram um estágio de desenvolvimento capaz de limitar o seu contínuo crescimento, devido à significativa redução no suprimento sedimentar proveniente dos sistemas praias adjacentes. Uma vez que a própria barreira costeira na qual os esporões encontram-se ancorados constitui-se na sua principal fonte de sedimentos (TOLDO, 1994).

Propõe-se, portanto, que a redução significativa de suprimento sedimentar, juntamente com as condições hidrodinâmicas atuais, não favorece o contínuo crescimento dos esporões arenosos analisados, estando estas feições atualmente submetidas a um retrabalhamento sedimentar induzido pela intensa ação erosiva (destrutiva) das ondas e as associadas correntes litorâneas.

A elevada hidrodinâmica sobre os bancos submersos pode ser evidenciada pela ausência da presença de vegetação, uma vez que a ação das ondas sobre os bancos constitui-se em um fator estressante para sua colonização e crescimento (DOYLE, 2001). Além disso, seus efeitos na destruição da crista dos esporões submersos foram identificados através da presença de grãos de areias médios e grossos com bom índice de seleção e assimetria negativa, sugerindo a retirada do material arenoso mais fino da crista (topo) dos esporões submersos (TOLDO, 1991).

Complementarmente, as seções transversais A-A' e B-B' sobre o esporão das Desertas (subdividido em pontal e banco), com gradientes mais suaves no flanco oeste e gradientes mais acentuados no flanco leste, e as seções transversais C-C' e D-D' sobre o esporão São Simão (subdividido em pontal e banco), com gradientes mais acentuados no flanco norte e gradientes mais suaves no flanco sul, indicam a ocorrência de transporte sedimentar para o flanco sul (Figura 3), principalmente devido à ação das ondas predominantes de NE sobre os bancos, em decorrência da sua disposição transversal ao eixo principal do corpo lagunar (NW-SE), e a rasa coluna d'água na crista dos esporões, constituindo-se, portanto, em obstáculos para a livre propagação das ondas geradas pelos ventos predominantes de NE (TOLDO, 1991, 1994).

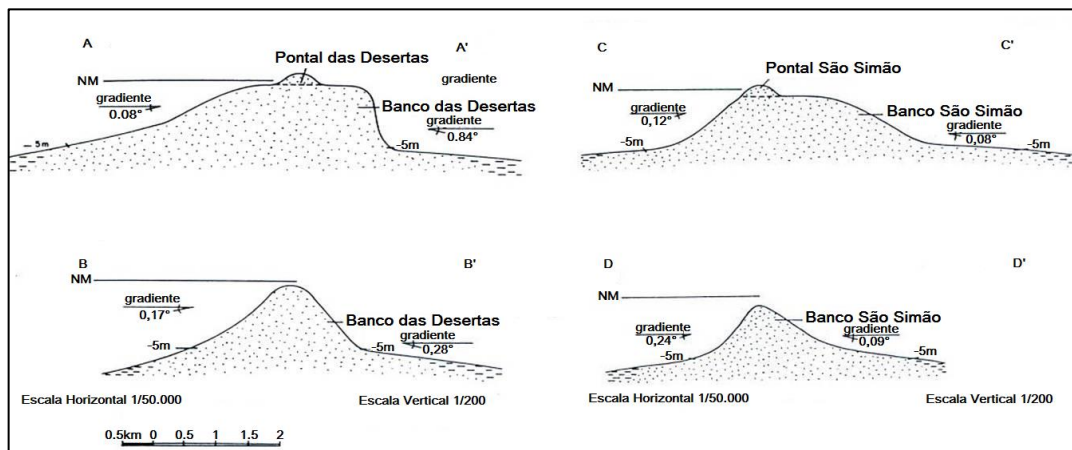


Figura 3. Perfis batimétricos do Pontal e Banco das Desertas (A-A' e B-B') e Pontal e Banco São Simão (C-C' e D-D').

Fonte: modificado de Toldo (1991).

Desta forma, presume-se que o processo erosivo sobre os depósitos de esporões arenosos submersos (bancos) está associado à redução no seu suprimento de sedimentos; e esta redução deve-se à estabilização da linha de costa dos arcos praias (área fonte de sedimentos). Em outros termos, propõe-se que, a significativa redução na taxa de suprimento de sedimentos para os esporões, além de ser em um fator limitante para o seu contínuo crescimento (prolongamento) no espaço, também constitui-se na causa da sua erosão.

1.4. OBJETIVOS DA TESE

1.4.1. Objetivo Geral

Analisar e quantificar o suprimento sedimentar para os esporões, e descrever e quantificar os processos morfodinâmicos e hidrodinâmicos (especificamente as ondas de gravidade) que regem o comportamento costeiro da linha de costa lagunar e dos depósitos de esporões arenosos cuspidados presentes na margem lagunar central oeste da Lagoa dos Patos, em escala de evento à escala histórica (COWELL; THOM, 1994).

1.4.2. Objetivos Específicos

- (A) Analisar e quantificar as mudanças da linha de costa em intervalos de tempo interanuais e de décadas, utilizando imagens de satélite LandSAT 5TM e 8^{OLI}, a fim de identificar se os arcos praias estão sofrendo representativa retração da linha de costa, uma vez que constituem-se na principal fonte de sedimentos para os esporões.
- (B) Descrever o agente modificador da morfologia costeira lagunar (as ondas de gravidade), por meio da investigação do controle da configuração da linha de costa cuspidada.

- (C) Correlacionar a morfologia submersa lagunar na geração, propagação e atenuação de onda, utilizando modelagem numérica (Delft 3D).
- (D) Identificar os principais padrões no transporte potencial de sedimentos ao longo da costa, induzidos por campos de ondas associados aos casos extremos e médios de vento em todas as direções.
- (E) Propor um modelo de balanço regional de sedimentos ao longo da margem lagunar central oeste.

1.5. LOCALIZAÇÃO E CARACTERIZAÇÃO DA ÁREA DE ESTUDO.

1.5.1. Contexto Regional – Planície Costeira do Rio Grande do Sul.

A presença de um grande número de lagoas costeiras (lagos e lagunas) é uma das características mais marcantes da paisagem da Planície Costeira do Rio Grande do Sul (TOMAZELLI *et al.*, 2011). A área de estudo, por sua vez, compreende o maior sistema lagunar da costa Sul Americana, abrangendo aproximadamente 10.000 km², com orientação preferencial NE-SW e uma profundidade média de 6 m (TOLDO, 1991).

A Lagoa dos Patos está situada na Planície Costeira do Rio Grande do Sul (PCRS), a qual é composta por dois principais tipos de sistemas deposicionais siliciclásticos: o sistema de leques aluviais e os sistemas do tipo laguna-barreira (Figura 4) (TOMAZELLI; DILLENBURG; VILLWOCK, 2000). A formação e a preservação dos quatro sistemas deposicionais do tipo laguna-barreira estão associadas a quatro flutuações glacio-eustáticas do nível do mar durante o Quaternário, responsáveis por grandes deslocamentos laterais da linha de costa na Planície Costeira do Rio Grande do Sul e na plataforma continental (VILLWOCK *et al.*, 1986). Cada sistema registra o pico de uma transgressão, seguida de um evento regressivo, sendo três de idade pleistocênica, Barreira I (há aproximadamente 400 ka), II (325 ka) e III (180 ka), e um de idade holocênica, Barreira IV (5 ka) (TOMAZELLI; DILLENBURG; VILLWOCK, 2000) (Figura 4b).

Os fatores preponderantes para a formação dos sistemas deposicionais do tipo laguna-barreira foram o baixo gradiente de declividade das feições fisiográficas (PCRS e plataforma continental), com a acentuada disponibilidade de sedimentos, associado a um regime de ondas de moderada a elevada energia e a baixa amplitude de maré (TOMAZELLI *et al.*, 2007).

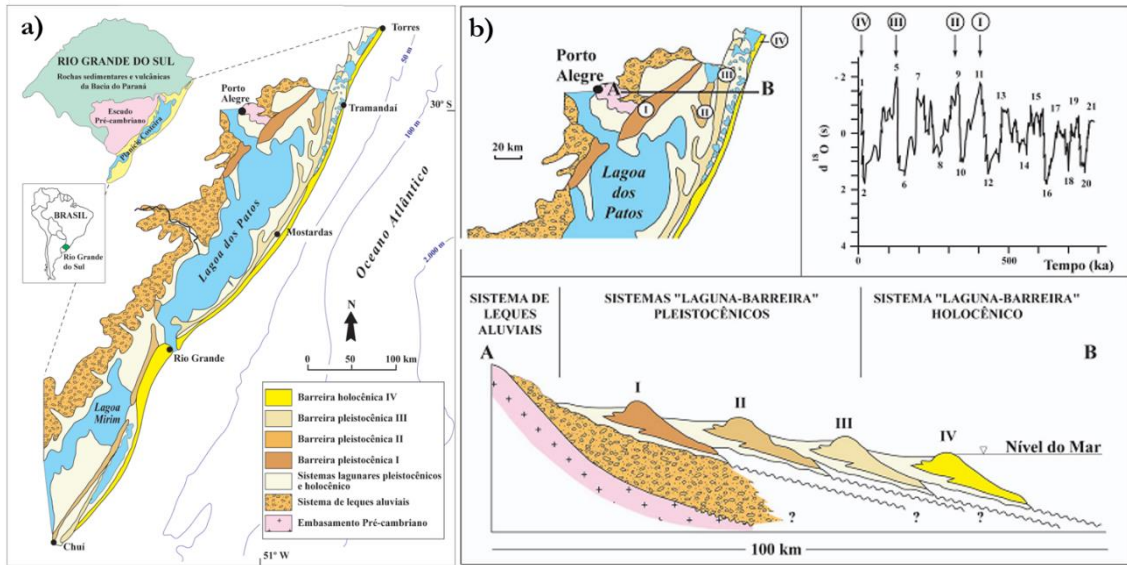


Figura 4. Figura ilustrando a) o mapa geológico simplificado da Planície Costeira do Rio Grande do Sul e, b) o perfil esquemático transversal aos sistemas deposicionais da Planície Costeira do Rio Grande do Sul. Fonte: modificado de Tomazelli *et al.* (2007).

1.5.2. Clima Regional

A PCRS está inserida na Zona Subtropical Sul, tendo seu clima controlado por dois centros de alta pressão: o Anticiclone Semipermanente do Atlântico do Sul e o Anticlone Móvel Polar (HASENACK; FERRARO, 1989). O Anticlone do Atlântico Sul situa-se em uma faixa de latitude entre 18° e 35°, e corresponde a um ativo centro de alta pressão, fonte de massas de ar quente e úmido, transportadas pelo vento de NE (CASTELÃO; MOLLER, 2003). O Anticlone Móvel Polar é alimentado por massas de ar frias provenientes da Antártica, deslocando-se no sentido SW-NE, em direção ao território brasileiro (TOMAZELLI, 1993).

O regime de ventos na região é de alta energia e de natureza bimodal, com os ventos predominantes incidindo de NE, intensificados durante os meses de primavera e verão, o que está associado ao fortalecimento do Anticiclone do Atlântico Sul devido ao aumento na intensidade da radiação solar no hemisfério sul (TOMAZELLI, 1990, 1993). No inverno, porém, o aumento da frequência de passagem dos sistemas frontais provoca um aumento na frequência da ocorrência de ventos do quadrante S (CASTELÃO; MOLLER, 2003).

1.5.3. Lagoa dos Patos

1.5.3.1. Morfologia Submersa e Sedimentologia do Sistema Lagunar

A morfologia do corpo d'água é caracterizada por quatro células limitadas por esporões arenosos rasos e, assim como outras lagoas, é conectada ao oceano por um canal de ligação estreito e longo, com 1-2 km de largura e 20 km de comprimento (MOLLER *et al.*, 1996).

Toldo (1991) individualizou o relevo submerso em duas principais unidades morfológicas: a margem lagunar e o fundo lagunar. A margem lagunar compreende a região entre o contorno lagunar e a isóbata de -5m; a margem oeste desenvolve-se sobre os depósitos costeiros que constituem o sistema de leques aluviais e o sistema laguna/barreira I, a margem norte desenvolve-se sobre os depósitos costeiros que constituem o sistema laguna/barreira II, e a margem leste desenvolve-se sobre os depósitos costeiros que constituem o sistema laguna/barreira III, ao passo que o fundo, ou piso lagunar, corresponde a um fundo plano que desenvolve-se da isóbata de -5m para porções mais profundas do corpo lagunar (TOLDO, 1994).

Sete classes granulométricas foram identificadas no relevo submerso da laguna – areia muito grossa, areia grossa, areia média, areia fina, areia muito fina, silte e argila –, sendo as margens lagunares essencialmente compostas por sedimentos arenosos e o fundo lagunar plano composto predominantemente por silte, e argila restrita ao setor sul (Figura 5) (TOLDO, 1994).

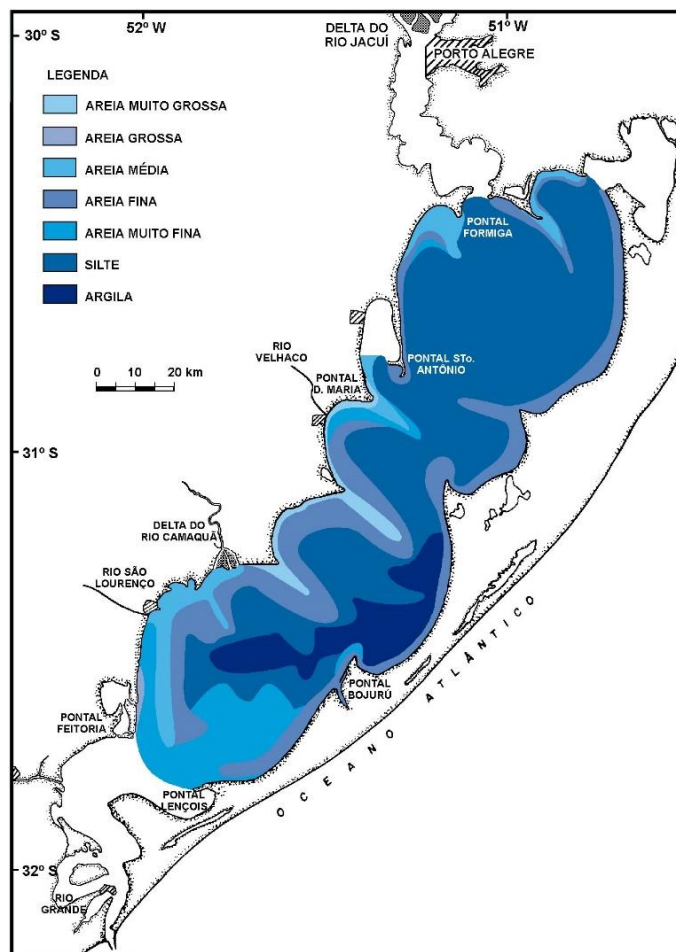


Figura 5. Mapa sedimentológico da margem e do fundo lagunar.
Fonte: Toldo (1994).

Para fins descritivos, Toldo (1991) classificou a porção emersa dos esporões como pontal e a porção submersa como banco. Neste estudo, os pontais e seus correspondentes bancos estão sendo referidos como esporões emersos e submersos, respectivamente.

Na PCRS, a presença de feições de esporões arenosos cuspidados restringe-se ao interior das margens lagunares (por exemplo, Lagoa dos Patos, Lagoa Mirim, Lagoa Mangueira). Na Lagoa dos Patos, os esporões cuspidados constituem-se no principal produto dos processos atuantes durante o Holoceno, tratando-se de simples extensões das praias fontes de sedimentos, que desenvolvem-se a partir da deriva litorânea resultante, devido à incidência oblíqua das ondas predominantes (TOLDO, 1994). A Lagoa dos Patos engloba um total de 13 esporões (Figura 6) que desenvolvem-se sobre uma superfície submersa rasa da ordem de aproximadamente -1m de profundidade, com distintas direções de crescimento; sendo que dois esporões encontram-se presentes na margem norte ([1] Pontal do Abreu e [2] Pontal das Desertas), seis na margem oeste ([3] Pontal Santo Antônio, [4] Pontal Dona Helena, [5] Pontal Dona Maria, [6] Pontal do Vitoriano, [7] Pontal do Quilombo e [8] Pontal da Feitoria), e cinco

na margem leste ([9] Pontal do Anastácio, [10] Pontal São Simão, [11] Pontal Cristóvão Pereira, [12] Pontal Bojurú e [13] Pontal dos Lençóis) (TOLDO, 1989).

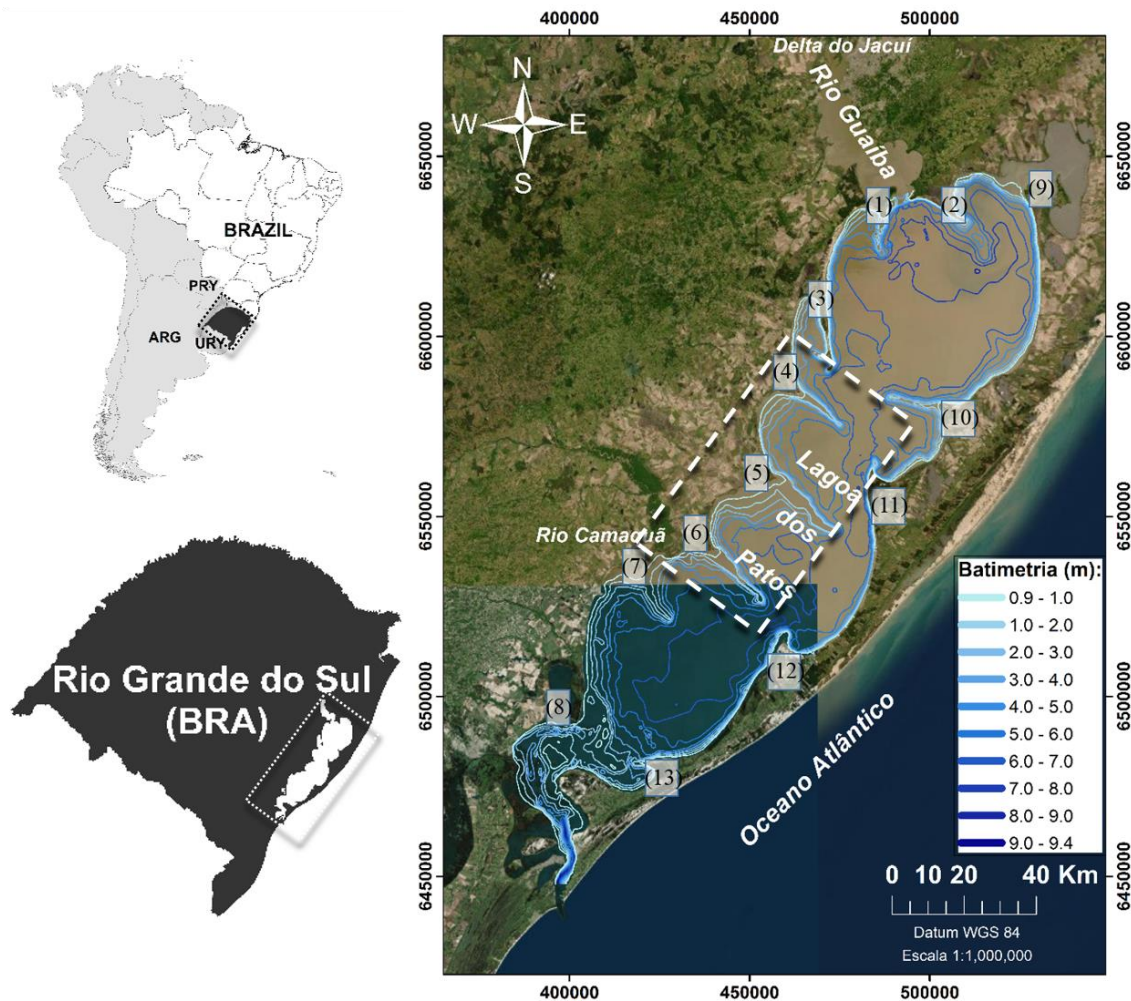


Figura 6. Mapa de localização da Lagoa dos Patos, demonstrando a presença e a extensão dos esporões arenosos presentes nas margens lagunares: 1. Pontal do Abreu, 2. Pontal das Desertas, 3. Pontal Santo Antônio, 4. Pontal Dona Helena, 5. Pontal Dona Maria, 6. Pontal do Vitoriano, 7. Pontal do Quilombo, 8. Pontal da Feitoria, 9. Pontal do Anastácio, 10. Pontal São Simão, 11. Pontal Cristóvão Pereira, 12. Pontal Bojurú e 13. Pontal dos Lençóis; com destaque para a área de estudo na margem central oeste da lagoa.

Fonte: elaboração da autora.

Base de dados: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, the National Centre for Space Studies (CNES)/Airbus DS, U.S. Department of Agriculture, U.S. Geological Survey, AeroGRID, IGN Spain, and the GIS User Community.

A laguna atua como uma bacia de compensação, pois representa uma zona de convergência da rede de drenagem da Bacia de Sudeste do Estado do Rio Grande do Sul e de Nordeste da República do Uruguai (TOLDO, 1994). Não se constitui, portanto, em um sistema fechado, uma vez que a fonte e a mobilidade dos sedimentos são, também, controladas pela importante contribuição hídrica da bacia de drenagem de sudeste (TOLDO *et al.*, 2006b).

Exibe um típico padrão de fluxo sazonal de média latitude, com maior fluxo de água doce no inverno e na primavera austral, e menor fluxo no verão e outono austral (MOLLER *et*

al., 2001). O principal contribuinte de água doce para a Lagoa dos Patos constitui-se no Rio Guaíba, desaguando a noroeste do corpo lagunar (cujos principais tributários constituem-se nos rios Jacuí, Sinos e Caí), e com uma contribuição muito menor o rio Camaquã na parte média (TOLDO *et al.*, 2000), além de outros menores afluentes como os rios Velhaco, São Lourenço, Pelotas e o canal de São Gonçalo.

Em termos de fontes de sedimentos, o Rio Guaíba contribui principalmente com lama, pois a descarga de areia produzida pela bacia de drenagem de Sudeste do Estado é retida no Delta do Rio Jacuí (TOLDO; ALMEIDA; CORRÊA, 2003).

E, conforme outros corpos lagunares alongados /ou “estrangulados”¹, a dinâmica de circulação é regida pelo regime de ventos e pela descarga fluvial (KJERFVE, 1986; MOLLER *et al.*, 2001; FERNANDES *et al.*, 2004; VAZ; MOLLER; ALMEIDA, 2006). Moller *et al.* (1996, 2001) destacam a importância da influência dos ventos na hidrodinâmica lagunar no seu efeito local e não-local. O primeiro associado à componente longitudinal dos ventos (NE/SW) que forçam o mecanismo de oscilação “*setup/ setdown*”, em que os ventos de NE ocasionam um rebaixamento do nível d’água na região norte e um empilhamento (elevação) na região sul, facilitando o fluxo de escoamento de vazante em direção ao mar, enquanto os ventos de SW produzem o efeito contrário, tornando-se mais importantes durante o outono e a primavera, quando os sistemas frontais penetram a região mais frequentemente, influenciando no fluxo para montante da laguna durante períodos de baixa contribuição fluvial, ao passo que a região central constitui-se na zona nodal (MOLLER *et al.*, 1996). O efeito não local do vento, ocasionado pelo mecanismo do transporte de Eckman, é responsável por variações no nível d’água na costa oceânica e, ambos os efeitos constituem-se em importantes fatores na troca de água entre a laguna e a plataforma continental (FERNANDES *et al.*, 2002).

As forças relativas à maré astronômica, por sua vez, restringem-se ao baixo estuário da Lagoa dos Patos, uma vez que os sinais de maré são fortemente atenuados ao adentrar no canal de Rio Grande, conforme demonstrado nos estudos de Moller *et al.* (1996) e Fernandes *et al.* (2004), o que é uma característica comum as lagunas do tipo alongadas ou/ “estranguladas” “*choked lagoons*” (KJERFVE, 1994), em decorrência da influência dos condicionantes geomorfológicos; Toldo (1994) destaca o comprimento do sistema estuarino (65 km), a profundidade do canal de Rio Grande (<15m) e a seção mínima desse canal (9.000 m²). Além

¹ Lagunas estrangulas “*choked lagoons*” (ou lagunas alongadas “*elongated lagoons*”): corpos lagunares formados por uma série de células elípticas interconectadas, ligados à costa oceânica adjacente por um único canal de acesso, longo e estreito, e normalmente desenvolvem-se ao longo de costas com elevada energia de onda, disponibilidade de sedimentos e, conseqüentemente com deriva litorânea significativa (KJERFVE, 1986).

de filtrar a maré astronômica, ele atenua a influência das ondulações incidentes na costa adjacente (FERNANDES *et al.*, 2004).

No interior da Lagoa dos Patos, por sua vez, a dinâmica do sistema é controlada principalmente pelo vento local (TOLDO, 1994; FERNANDES *et al.*, 2004).

1.5.3.2. Regime de Ondas.

Os primeiros estudos de predição de ondas ao longo do litoral da Lagoa dos Patos foram conduzidos por Toldo (1994) e Toldo *et al.* (2006a), com base em uma extensa campanha de medição de dados horários de vento realizada durante o ano de 1988 ao longo das margens lagunares, cujos resultados podem ser vistos pelas rosas de ventos e ondas por período sazonal para cada estação de medições de dados (Figura 7).

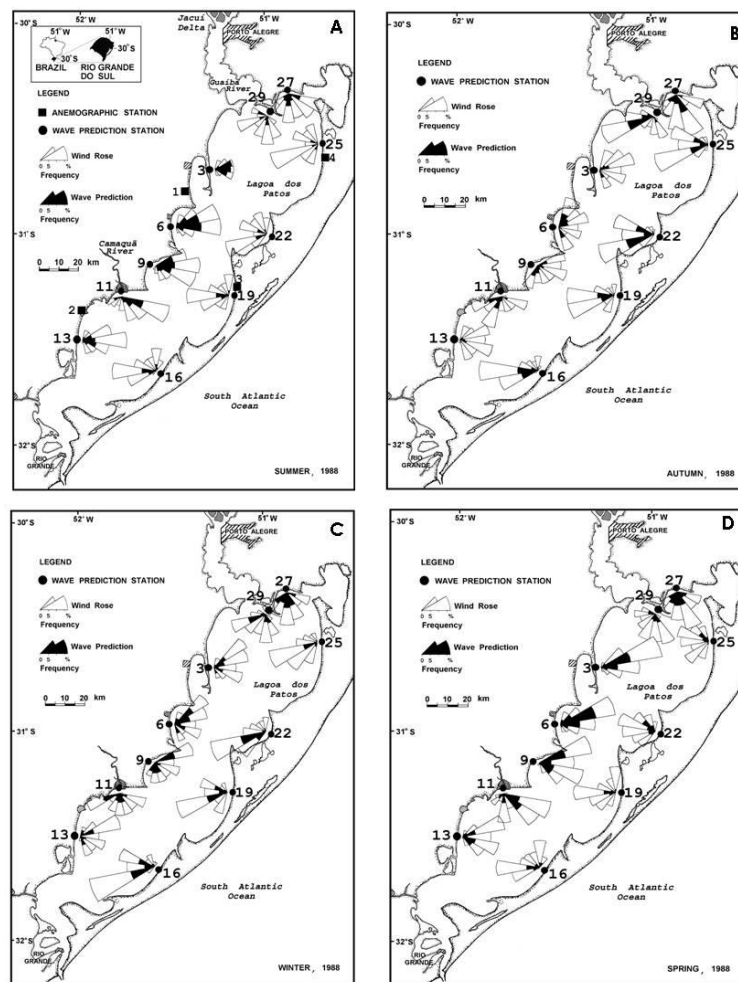


Figura 7. Distribuição sazonal de frequência de direção de ondas e ventos para cada estação de predição de onda ao longo da laguna, durante os meses de (A) verão, (B) outono, (C) inverno e (D) primavera para o ano de 1988. Fonte: Toldo *et al.* (2006a).

O estudo de Toldo *et al.* (2006a) concluiu que, na margem oeste, a direção predominante de ondas é de NE e ENE em decorrência dos ventos dominantes de NE no verão e na primavera,

com médias das alturas significativas entre 0,5-0,7 m e períodos entre 2,7s e 3,3s, enquanto que na margem leste os ventos prevalecentes são de WNW e WSW. Ademais, a análise do fluxo direcional de energia de onda sobre as margens lagunares, demonstrou que as estações de predição das ondas da margem leste recebem menor intensidade do fluxo de energia anual, porém estão submetidas à ação de ondas de tempestade com maior frequência que as estações de ondas da margem oeste (Figura 7c) (TOLDO, 1994).

O primeiro estudo de modelagem de ondas na Lagoa dos Patos foi realizado por Simão (2015), com o emprego do modelo SWAN (“*Simulating Waves Nearshore*”), constituindo-se em um extenso estudo experimental que atestou a capacidade do modelo de simular o comportamento ondulatório da laguna, assim como observou que os esporões são responsáveis por uma descontinuidade nos campos de ondas, de acordo com os estudos prévios de Toldo *et al.* (2006a). Em seguida, Lemke (2015) realizou o primeiro estudo de modelagem de ondas, com a validação de dados medidos em campo pelo ondógrafo *Waverider Datawell Mark III*, especialmente focado para a dinâmica da foz do Arroio Carahá. O ondógrafo foi fundeado a partir de uma iniciativa da Comissão Intergovernamental de Oceanografia (IOC-UNESCO) coordenada pela Universidade Federal de Rio Grande, através do projeto “Rede Ondas, Rede de Monitoramento de Ondas em Águas Rasas” do Sistema de Observação do Oceano Global (GOOS/ Brazil).

Dentre os fatores limitantes para a geração de ondas no sistema lagunar, Toldo (1994) destacou a elevada frequência de ventos com velocidades inferiores a 2 m/s, e secundariamente a curta duração de ventos com velocidades superiores a 2 m/s, além da geometria da bacia, em que a pista de vento e a profundidade exercem um maior controle no crescimento de ondas para uma dada condição de vento.

1.5.3.3. Dinâmica Sedimentar

A magnitude das correntes longitudinais e o transporte sedimentar associado são favorecidos pelo extenso e suave gradiente da zona de surfe, e pela ocorrência de ondas com moderada altura e elevados ângulos de incidência com relação à costa (TOLDO; ALMEIDA; CORRÊA, 2003).

De acordo com os estudos de Toldo (1994), o transporte sedimentar transversal é primeiramente controlado pelo tamanho do sedimento: maiores tamanhos de grãos (0,50 mm) apresentam sentido preferencial de transporte para a praia emersa, e menores tamanhos de grãos (0,125 mm) apresentam sentido preferencial para a antepraia inferior.

Com relação ao transporte sedimentar longitudinal, Toldo, Almeida e Côrrea (2003) identificaram que as correntes e o associado transporte de sedimentos estão de acordo com as direções dominantes de vento, ventos predominantes de NE e ENE na margem oeste com deriva litorânea resultante para sul, e ventos dominantes de WSW na margem leste com deriva resultante para norte (Figura 8).

A margem oeste (objeto de estudo da presente Tese) é caracterizada por uma distribuição de sedimentos de fundo com maiores tamanhos de grãos do que a distribuição sedimentar da margem leste, apresentando transporte transversal com sentido preferencial para a praia emersa e transporte sedimentar longitudinal resultante para sul (Figura 8) (TOLDO, 1994).

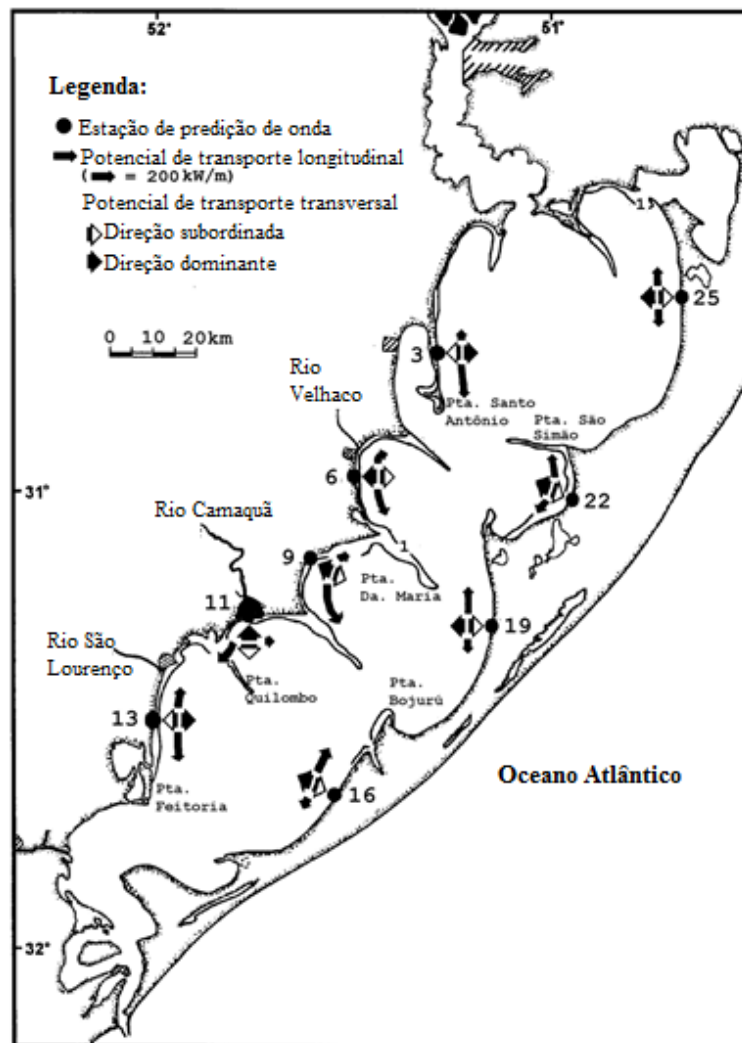


Figura 8. Potencial de transporte de sedimentos longitudinal e transversal ao longo da linha de costa da Lagoa dos Patos para o ano de 1988, com as setas preenchidas indicando a direcionalidade dominante do trânsito sedimentar. Fonte: modificado de Toldo, Almeida e Côrrea (2003).

Toldo (1994) também identificou que as margens da Lagoa dos Patos são favorecidas para o desenvolvimento de bancos arenosos, em decorrência do seu suave gradiente, do elevado estoque de sedimentos subaquosos e da ausência de marés astronômicas, cujas morfologias correspondem ao que tem sido documentado por praias oceânicas dominadas por ondas (Figura 9).



Figura 9. Fotografia aérea da margem lagunar leste, célula 1, com a presença de bancos transversais e secundariamente bancos paralelos, a uma distância de aproximadamente 500 m da linha de praia, e extensivos leques de sobrelavagem “washover” na planície adjacente.
Fonte: Toldo (1994).

Conforme pode-se observar na figura 9, a distância entre os bancos paralelos e a linha de costa é concordante com o sentido potencial de transporte transversal na margem leste, com erosão na antepraia superior e deposição na antepraia inferior, um dos mecanismos responsáveis pela retrogradação das praias lagunares nas estações de ondas que apresentam um processo de transporte sedimentar preferencial para a antepraia inferior (TOLDO, 1994), como é o caso das estações na margem leste (25, 22, 19, 16) e das estações na primeira e quarta células lagunares da margem oeste (3 e 13). Já as estações localizadas na região central da margem oeste da laguna (9, 11 e 27) apresentam sentido potencial de transporte sedimentar transversal dominante para a praia emersa (Figura 8) (TOLDO; ALMEIDA; CÔRREA, 2003).

Tanto a erosão costeira quanto a migração dos bancos em direção à praia produzem um significativo suprimento de sedimentos para a zona de surfe, os quais ficam expostos ao intenso potencial de transporte sedimentar longitudinal e, comparativamente, a magnitude do transporte longitudinal ao longo das praias lagunares é uma ou duas ordens maior do que o transporte transversal (TOLDO, 1994).

CAPÍTULO 2. MORFODINÂMICA DE ESPORÕES ARENOSOS CUSPIDADOS “CUSPATE SPITS” NA MARGEM DE SISTEMAS LAGUNARES

2.1. MORFODINÂMICA COSTEIRA

A morfodinâmica costeira pode ser entendida como um método quantitativo-empírico de perspectiva sistêmica cujo objetivo central constitui-se na análise integral do sistema costeiro (WRIGHT; THOM, 1977). Investiga a ação da dinâmica dos fluidos na morfologia através do transporte de sedimentos, ocasionando mudanças morfológicas que, por sua vez, alteram a ação do fluido, modificando os padrões de transporte e produzindo novas mudanças morfológicas. Pode, portanto, ser entendida como um complexo coajuste mútuo entre os processos dinâmicos e a topografia, o qual atua por meio do transporte e da consequente redistribuição dos sedimentos ao longo do prisma praial, nos sentidos transversal e longitudinal, em resposta às forças físicas – mecanismos que resultam do fato de o sistema estar constantemente esforçando-se para atingir uma condição de equilíbrio ou “*otipma*”, na qual tanto o comportamento do “processo” como a “forma” podem atingir uma condição de estabilidade “máxima” (WRIGHT; THOM, 1977).

O prisma praial é a região na qual ocorre a troca de sedimentos e consequentes mudanças morfológicas, limitado entre a profundidade de fechamento e alguma mudança morfológica brusca na praia. No presente trabalho de Tese, está sendo avaliado o transporte de sedimentos na porção submersa do prisma praial, entre o contorno da linha de costa lagunar e a profundidade de fechamento – aproximadamente 3,3 m, utilizando a formulação de Hallermeier (1981) para a delimitação do limite litorâneo.

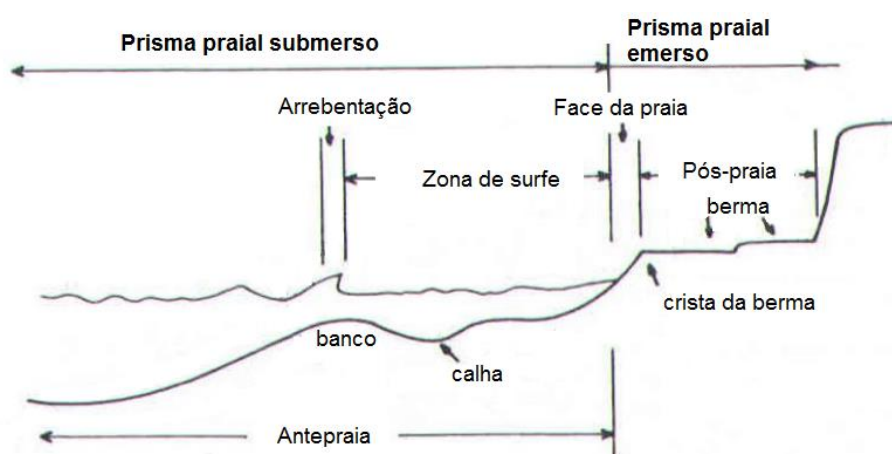


Figura 1. Diagrama geral simplificado do perfil de praia individualizando a porção submersa e emersa do prisma praial.

Fonte: modificado de Muehe (1998).

A morfodinâmica costeira constitui-se, portanto, em um importante método de estudo, que possibilita a melhor compreensão do comportamento da zona costeira, seus processos moduladores e suas inter-relações mútuas, auxiliando na melhora da capacidade científica para a predição das mudanças costeiras em resposta às forças motrizes aplicadas em diferentes escalas temporais e espaciais. E a evolução costeira é o produto de processos morfodinâmicos que operam em resposta às mudanças nas condições externas (WRIGHT; THOM, 1977). O transporte de sedimentos, por sua vez, fornece o mecanismo de acoplamento dependente do tempo pelos quais os ajustes entre a morfologia e a hidrodinâmica ocorrem, isto é, o regime de energia (a dinâmica do fluido) rege o transporte de sedimentos que resultará nas mudanças morfológicas ao longo do tempo (COWELL; THOM, 1994) (Figura 2).

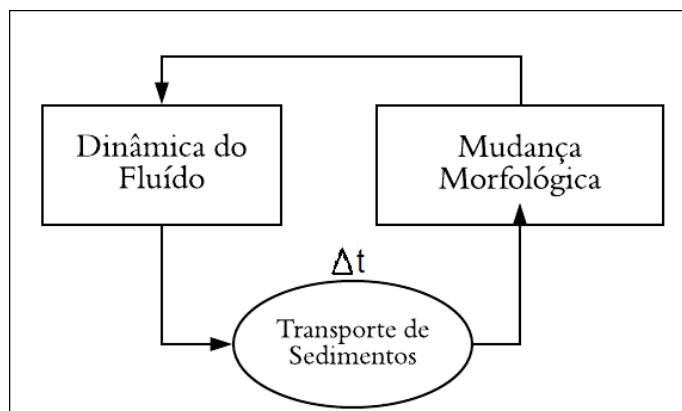


Figura 2. Ilustração dos componentes primários envolvidos na morfodinâmica costeira, indicando o ciclo de retroalimentação contínuo, o “*feedback loop*”, entre a forma e o processo, o qual é responsável pela complexidade fundamental na evolução costeira.

Fonte: modificado de Cowell e Thom (1994).

A retroalimentação pode tanto ser negativa como positiva. Retroalimentações negativas conferem propriedades de auto-regulação que ocorrem em resposta a pequenas perturbações para restaurar a homeostase, e, retroalimentações positivas conferem propriedades de auto-organização, o que implica crescimento de uma instabilidade, resultando em novos modos de operação (WRIGHT; THOM, 1977; COWELL; THOM, 1994). Inversões de retroalimentação “*feedback reversals*” marcam fronteiras/limiares “*thresholds*” no comportamento morfodinâmico (COWELL; THOM, 1994).

A abordagem morfodinâmica envolve a análise das seguintes categorias, as quais exibem mútua interdependência: 1. as características e a variabilidade espaço-temporal das condições do ambiente costeiro; 2. os processos morfodinâmicos e hidrodinâmicos de interação e as transformações que ocorrem dentro do sistema costeiro para produzir os observados padrões morfológicos e as mudanças morfológicas e; 3. as sequências evolutivas de curto e

longo prazo, que, em última análise, produzem as morfologias e estratigrafias preservadas, e que progressivamente modificam os ambientes dinâmicos e as combinações dos processos (WRIGHT; THOM, 1977).

A modelagem do comportamento costeiro de larga-escala consiste em uma tentativa de simular a morfodinâmica da mudança costeira em escalas de tempo e espaço adequadas ao seu manejo e previsão (FRENCH *et al.*, 2016). Tais modelos são regulados pela captura de fortes alças de retroalimentações que governam o comportamento das formas de relevo da superfície terrestre, constituindo-se em ferramentas computacionalmente eficientes e facilmente aplicadas dentro de uma estrutura probabilística, as quais têm demonstrado significativa eficácia na representação do comportamento costeiro emergente em escala de paisagem (MAANEN *et al.*, 2016) (Figura 3).

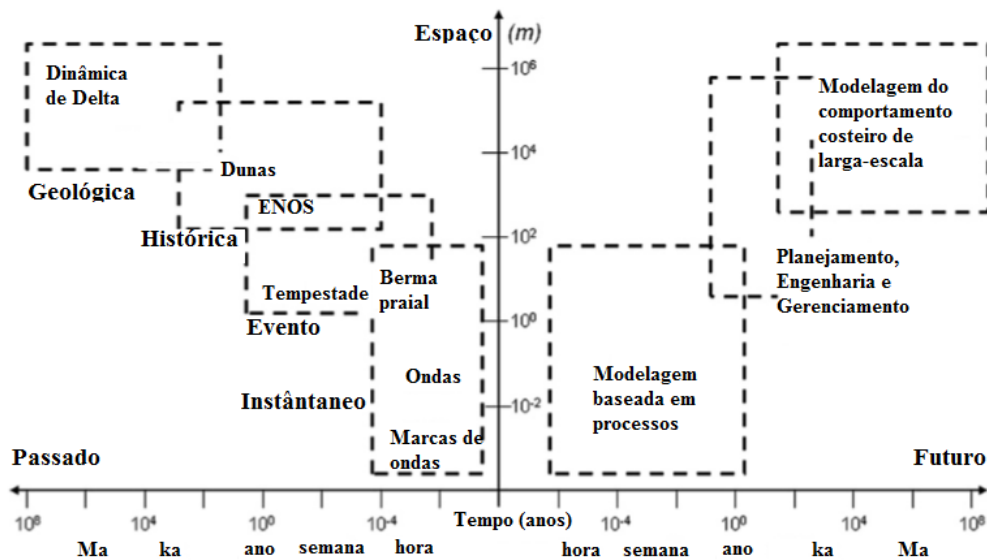


Figura 3. Representação hierárquica das escalas espaciais/temporais das mudanças no ambiente costeiro e a indicada abordagem metodológica a ser empregada.

Fonte: modificado de uma adaptação de MAANEN *et al.*, (2016), com base em Cowell e Thom (1994), adaptado por Woodroffe (2003) no lado esquerdo, Gelfenbaum e Kaminsky (2010) no lado direito.

De acordo com Cowell e Thom (1994), as escalas nas quais os processos morfodinâmicos operam podem ser agrupadas em quatro classes: 1. instantânea, envolve alterações morfológicas primárias pela ação de ondas e marés; 2. evento, envolve a formação de estruturas sedimentares e sequências deposicionais, em resposta à processos que operam em uma escala temporal que pode ir de um único evento, como uma tempestade, até variações sazonais das condições ambientais; 3. histórica ou de engenharia, que envolve a evolução de diversas alterações morfológicas sobre a atuação de várias flutuações das condições ambientais, implicando vários ciclos nos processos fundamentais responsáveis pelo transporte de

sedimentos e; 4. geológica, resultado de uma tendência média das condições ambientais sobre milênios (ver Figura 3).

Neste trabalho, serão avaliados especificamente os processos morfodinâmicos ocorrentes em escala de evento (anual), através de modelagem numérica baseada em processos (modelagem reducionista), utilizando o pacote de modelos Delft 3D, até a escala histórica, com a análise da variação na posição da linha de costa, envolvendo um período de três décadas.

2.2. ESPORÕES CUSPIDADOS

O termo “esporões cuspidados” (“*cusped spits*”) normalmente refere-se a feições geomorfológicas da linha de costa com formato triangular (cuspidado), desenvolvidas no interior de corpos d’água restritos, cuja geometria inicial da bacia exerce importante controle na pista de vento, ocasionando uma elevada proporção de incidência de ondas com ângulos oblíquos (φ°) com relação à orientação geral da linha de costa (θ°), o que gera uma maximização na deriva litorânea de sedimentos, acarretando intensos processos erosivos e deposicionais, resultando na reorientação da linha de costa para as direções de ondas predominantes (ZENKOVITCH, 1959; ROSEN, 1975; DELANEY, 1965; TOLDO, 1989, 1994).

A formação dos esporões cuspidados ocorre à medida que o setor costeiro à montante “*updrift*” é erodido, formando uma reentrância praial com formato arqueado (arco praial) conforme o esporão cresce lateralmente, no sentido da deriva litorânea resultante “*downdrift*”, projetando-se para o interior do corpo hídrico em forma de cúspide, o que é resultado do processo de reorientação da linha de costa induzido por elevados gradientes na deriva litorânea de sedimentos devido à dominante ocorrência de incidência de ondas com ângulos oblíquos com relação à orientação geral da linha de costa.

Conforme o esporão projeta-se para o interior do corpo d’água uma zona de sombra é formada no setor costeiro a sotamar, protegendo a porção adjacente da costa das ondas predominantes. Enquanto isso, “ondas subordinadas”² atuam no flanco a sotamar ocasionando transporte líquido de sedimentos na direção oposta, preenchendo a concavidade formada entre o esporão e o setor costeiro na zona de sombra, processo responsável pela formação de menores cordões litorâneos de configuração arqueada (ZENKOVITCH, 1959).

² Ondas subordinadas: Zenkovitch (1959) refere-se a “ondas subordinadas” como ondas de menor energia que penetram na zona de sombra do esporão. No trabalho de Alves (2006), são consideradas como as ondas que representam a segunda moda da distribuição de frequência, atuando no sentido oposto das ondas predominantes.

Os esporões localizados em posições mais favorecidas (isto é, em setores costeiros mais expostos à incidência de ondas oblíquas), crescem em detrimento dos esporões localizados nos setores mais abrigados e o processo se repete ao longo da costa (ZENKOVITCH, 1959; ROSEN, 1975). Ashton, Murray e Arnoult (2001) acrescentaram que o efeito de sombreamento de onda promovido pelas feições de maior amplitude, abriga as feições adjacentes (de menor amplitude) da incidência de ondas oblíquas (ou anti-difusivas³), e, por sua vez, as feições de menor amplitude experienciam um regime de ondas de baixos ângulos, tendo o seu crescimento inibido.

Ao atingirem uma amplitude finita, as feições começam a interagir umas com as outras através do mecanismo morfodinâmico de sombreamento de onda “*wave-sheltering effect*”, resultando na auto-organização da linha de costa. Processo responsável pela formação de feições geomorfológicas rítmicas de larga-escala da linha de costa, cuja escala espaço-temporal varia de dezenas a centenas de quilômetros (10 - 10^2 km) e de décadas a milênios (10^1 - 10^3 anos), respectivamente (ASHTON; MURRAY; ARNOULT, 2001).

Os esporões constituem-se nas formas de relevo mais dinâmicas da superfície terrestre, abrigando uma elevada complexidade de processos de formação (ZENKOVITCH, 1959; CARTER, 1988; ORFORD, 2004; UDA, 2005; RANDAZZO, JACKSON; COOPER, 2015). São compostos por sedimentos provenientes de diferentes origens e com diferentes tamanhos de grãos, desde areia fina até seixos e, inclusive, pedregulhos; sendo que os esporões compostos por sedimentos do tamanho areia são mais comumente encontrados em várias regiões do Planeta (RANDAZZO; JACKSON; COPPER, 2015).

Os esporões cuspidados “*cusped spits*” tendem a ser melhor desenvolvidos em ambientes dominados por ondas geradas pelo vento local “*sea waves*”, encontrando-se, portanto, situados mais comumente em ambientes costeiros abrigados e semiabrigados, e menos comuns em ambientes costeiros abertos dominados por ondas, no qual as ondulações “*swell waves*” são eficientemente refratadas antes de atingirem a linha de costa (RANDAZZO; JACKSON; COOPER, 2015).

As lagunas são definidas como corpos d’água rasos separados do oceano por uma barreira, e conectados ao menos intermitentemente com o oceano adjacente por um ou mais canais restritos, usualmente orientados paralelamente à costa (KJERFVE, 1994). Normalmente

³ Ondas antidifusivas: Frentes de ondas que se aproximam da costa com elevada obliquidade antes de sofrerem os processos de refração e empolamento, podendo variar entre os ângulos de incidência de $(\varphi-\theta)= 34^\circ$ de Kamphuis (1991) à $(\varphi-\theta)= 52^\circ$ de Baillard (1984), dependendo da equação para o transporte longitudinal de sedimentos utilizada.

são consideradas feições efêmeras na escala de tempo geológica, com um ciclo de vida da ordem de milhares de anos (COOPER, 1994). O estudo de lagunas “*coastal lagoons*” está intrinsicamente conectado com o da barreira que a segmenta, cujos principais fatores determinantes de sua origem e manutenção constituem-se: 1. nas oscilações do nível do mar; 2. na dinâmica do prisma praiial; 3. na amplitude de maré (MARTIN; DOMINGUEZ, 1994).

Nos estágios iniciais de desenvolvimento de um sistema lagunar, suas margens estão mais susceptíveis aos agentes moduladores das mudanças morfológicas (ondas e as correntes induzidas por ondas) e, conforme a sua atuação na erosão de determinados setores e deposição em outros em ocorre, há uma tendência ao longo do tempo de o sistema lagunar atingir uma condição de equilíbrio, um balanço entre a forma e o processo, que é dependente das características dos sedimentos (ex.: tamanho de grão) e da efetividade das ondas no processo erosivo (SILVA *et al.*, 2004; LANE, 2019).

Zenkovitch (1959) foi o primeiro pesquisador a delinear o processo de formação e desenvolvimento dos esporões cuspidados em lagunas alongadas, dentro de um quadro conceitual mais amplo – tendo como base os trabalhos de De-Lamblardie (1789), Gilbert (1885), Johnson (1919) e Johnson (1942).

- **O Papel da Deriva Litorânea**

Gilbert (1885 *apud* EVANS, 1942), aparentemente, foi o primeiro pesquisador a destacar que somente as correntes longitudinais induzidas por ondas são capazes de explicar a formação dos esporões, em especial para as feições compostas por sedimentos grosseiros. Os trabalhos de Johnson (1919) e Johnson (1942 *apud* ZENKOVITCH, 1959) abordaram o papel da deriva litorânea no transporte de sedimentos a partir das indentações em direção às projeções da linha de costa e a reconhecer a importância da ação do fluxo “*swash*” e refluxo “*backwash*” das ondas no transporte sedimentar.

De-Lamblardie (1789 *apud* ZENKOVITCH, 1959), aparentemente, foi o primeiro pesquisador a sugerir que o fluxo sedimentar longitudinal é maximizado sob a incidência de ondas com ângulos oblíquos (~45°) com relação à costa, o qual pode variar dependendo da granulometria e da declividade do substrato. Tal postulado foi posteriormente ratificado por Bruun (1954 *apud* ASHTON; MURRAY; LITTLEWOOD, 2007) em um quadro quantitativo, a partir de experimentos laboratoriais, edificando o conceito de que os esporões crescem a partir da deriva litorânea, e destacando a importância que a influência da obliquidade do ângulo de incidência de onda exerce na maximização do transporte sedimentar longitudinal, na forma de

equilíbrio da linha de costa, e no potencial de formação de “projeções” localizadas a jusante “*downdrift*” desse ponto de maximização.

O enfoque dos estudos pioneiros tinha como base as análises geomorfológicas e os registros estratigráficos, carecendo de uma maior quantificação e elucidação dos processos físicos moduladores da sua evolução morfológica (EVANS, 1942), principalmente devido às limitações de instrumentação disponíveis na época.

A importância da análise geomorfológica pode ser vista no trabalho precursor de Zenkovitch (1959). A partir de uma extensa investigação de esporões rítmicos na Península de Chucki (Rússia), o autor forneceu um modelo qualitativo para a descrição da gênese e dos processos responsáveis pelo desenvolvimento de esporões em lagunas alongadas – também referidas na literatura como “lagunas estranguladas” (KJERFVE, 1994).

2.2.1. Modelo conceitual de evolução de esporões cuspidados em lagunas alongadas (ZENKOVITCH, 1959)

O quadro conceitual proposto por Zenkovitch (1959) argumenta que, nos estágios iniciais de desenvolvimento dos esporões, os setores praias ao longo do eixo lagunar principal estão sujeitos à elevada proporção de ondas incidentes com ângulos oblíquos com respeito à tendência geral de orientação da linha de costa, resultando em intensos processos erosivos (destrutivos) e deposicionais (construtivos), que ocasionam a formação de esporões incipientes com formatos assimétricos, e cujas terminações projetam-se em direção às extremidades da laguna, enquanto na região central esporões simétricos são encontrados (Figura 4a).

Nos estágios intermediários, o clima de ondas da laguna começa a sofrer modificações conforme o esporão cresce lateralmente projetando-se para o interior do corpo lagunar, e constituindo-se em obstáculos para a livre propagação das ondas lagunares. Para o caso de ambos os lados das margens lagunares serem compostas por sedimentos inconsolidados, os esporões se desenvolvem de forma pareada. O desenvolvimento de esporões pareados resulta em maiores modificações nos campos de ondas associados aos ventos que sopram ao longo do eixo lagunar principal (longitudinal) (ZENKOVITCH, 1959) (Figura 4b), desta maneira diminuindo as alturas de ondas incidentes ao longo da costa e, por sua vez, seu potencial erosivo das praias lagunares.

Em contrapartida, os campos de ondas associados aos ventos atuantes ao longo do eixo transversal da laguna sofrem pouca alteração, podendo, inclusive, tornarem-se mais

energéticos, em decorrência do aumento na pista de vento para esta direção de geração de onda. Este aumento na pista de vento é decorrente da acentuada erosão dos arcos praias conforme os esporões pareados crescem lateralmente, fator que acarreta no “alargamento” das células lagunares (Figura 4b).

A efetividade da deriva litorânea ao longo do sistema praias compostos pelos arcos praias e pelos esporões diminui radicalmente até atingirem uma configuração de estabilidade (ZENKOVITCH, 1959). Por configuração de estabilidade, o autor compreende que a distribuição direcional das ondas resultantes no interior do corpo lagunar não mais se constitui em duas componentes opostas, orientadas com ângulos oblíquos com respeito à costa. Isto é, neste estágio, as resultantes das ondas adquirem diferentes direções em diferentes setores dos arcos praias entre os esporões, e não apresentam incidência oblíqua em nenhum segmento costeiro, de modo que a tendência para o desenvolvimento de formas complexas da linha de costa é substituída pela tendência de suavização e arredondamento (Figura 4c).

O modelo de evolução lagunar proposto por Zenkovitch (1959) tem como produto final a completa segmentação da laguna (Figura 4c), sendo que, quanto mais estreito o corpo lagunar, mais cedo o sistema se estabiliza.

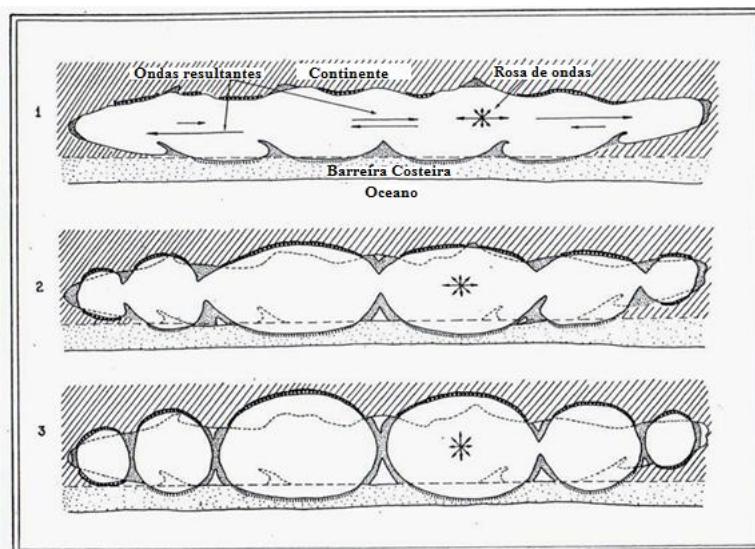


Figura 4. Ilustração do modelo conceitual proposto por Zenkovitch (1959): (1) as setas no corpo de água representam a magnitude da ação do sistema de ondas, (2) a rosa de ondas é elíptica, mas menos alongada que no primeiro estágio de desenvolvimento, (3) a rosa de ondas é aproximadamente arredondada, não mais constituindo-se em duas componentes opostas orientadas com ângulos oblíquos com respeito à costa. Fonte: modificado de Zenkovitch (1959).

Este modelo é referência na literatura científica até os dias atuais, em especial após a ratificação, assim como a maior elucidação dos processos morfodinâmicos regentes da sua evolução morfológica, dentro de um quadro quantitativo, por meio do emprego de modelos do

tipo 1-Linha. Trata-se de uma modelagem exploratória (sintetista) baseada em estudos de probabilidade, na fórmula semiempírica CERC (SPM, 1984) para o transporte longitudinal de sedimentos e no princípio da conservação dos sedimentos (LARSON, HARSON; KRAUS, 1997), associados à “opinião especialista”, para a investigação do comportamento costeiro de larga escala.

2.2.2. Estudos de esporões cuspidados ocorrentes na natureza.

Os estudos de Zenkovitch foram complementados pelos trabalhos de Rosen (1972; 1975), e por outros estudos de esporões cuspidados individuais (TOLDO, 1989, 1991, 1994; MCNINCH; WELLS, 1999; MCNINCH; LUETTICH, 2000; PARK; WELLS, 2005), de experimentos laboratoriais (PETERSEN; DEIGAARD; FREDSOE, 2008; UDA; SERIZAWA; MIYAHARA, 2014), e de modelos matemáticos capazes de simular o comportamento costeiro de larga-escala (ASHTON; MURRAY; ARNAULT, 2001; ASHTON; MURRAY, 2006a, 2006b; ASHTON *et al.*, 2009; MURRAY; ASHTON, 2013).

Os trabalhos de Rosen (1972, 1975) demonstraram, por meio de medições de correntes longitudinais na costa cuspidada da laguna de Nantucket (Figura 5), a ocorrência de transporte sedimentar líquido das concavidades praias para a terminação dos esporões, processo construtivo para o desenvolvimento dos esporões cuspidados. O autor também assume que esse processo é responsável pela manutenção da forma cuspidada da costa, ao passo que as correntes de maré, que são mais intensas nas terminações dos esporões emersos e submersos, atuam como um fator destrutivo no processo de formação dos esporões cuspidados.

Para o caso da laguna de Nantucket Harbor, MA-EUA, Rosen (1972, 1975) caracteriza o sistema lagunar como em equilíbrio, devido à atuação aproximadamente igual dos agentes construtivos (as correntes longitudinais induzidas pelas ondas) e destrutivos (as correntes de marés). Ademais, o autor complementa que as intensificações das correntes de maré nas extremidades livres dos esporões constituem-se em um fator limitante para a segmentação do corpo lagunar, de modo que a tendência de segmentação lagunar ocorre apenas em ambientes costeiros com baixa amplitude de maré.



Figura 5. Laguna de Nantucket Harbor, com aproximadamente 10 km de comprimento e largura variando entre 1 e 3 km.

Fonte: elaboração da autora.

Base de dados: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, the National Centre for Space Studies (CNES)/Airbus DS, U.S. Department of Agriculture, U.S. Geological Survey, AeroGRID, IGN Spain, and the GIS User Community.

À semelhança da Lagoa dos Patos, as direções de ventos dominantes na laguna de Nantucket Harbor (MA, EUA) são paralelas ao eixo lagunar principal, resultando na formação de esporões arenosos cuspidados bem desenvolvidos (ROSEN, 1975). Diferentemente do que, no geral, ocorre na Lagoa dos Patos, a atuação dos ventos dominantes é aproximadamente proporcional, resultando em semelhantes proporções no transporte sedimentar longitudinal proveniente de direções opostas, ocasionando a formação de esporões cuspidados com elevada simetria.

Complementarmente, mesmo que as direções de vento dominantes não sejam paralelas ao eixo lagunar principal (longitudinal), o maior comprimento da pista de vento nesta direção resultará na geração de ondas de maior amplitude do que as geradas pelos ventos que sopram ao longo do menor eixo lagunar (transversal) (ROSEN, 1982; ASHTON *et al.*, 2009).

Rosen (1975) diferenciou ainda “*cusplate spits*” de “*cusplate forelands*”: o primeiro termo referindo-se a feições geomorfológicas formadas através do processo de reorientação da linha de costa no interior de corpos d’água restritos; o segundo na costa oceânica aberta.

Entretanto, o termo “*cusplate foreland*” também é encontrado na descrição de esporões cuspidados presentes na margem terrestre de corpos d’água costeiros.

Feições geomorfológicas de esporões cuspidados são encontradas no interior de sistemas lagunares, como na ilha de Saint Lawrence, Alasca (FISHER, 1955; PRICE; WILSON, 1956); na Península de Chucki (Rússia); na província de Kwazulu-Natal (África do Sul) (ZENKOVITCH, 1959); na laguna de Nantucket Harbor, MA-EUA (ROSEN, 1972, 1975, 1982); na Lagoa dos Patos, RS-Brasil (DELANEY, 1965; TOLDO, 1989, 1991, 1994); na Lagoa de Araruama, RJ-Brasil (ALVES, 2006; ALVES *et al.*, 2006); na Lagoa Mangueira, RS-Brasil; e na Lagoa da Conceição, SC-Brasil; em mares marginais, como na costa norte do mar de Azov, Ucrânia (ZENKOVITCH, 1959; ASHTON, MURRAY, ARNAULT, 2001); e na costa oceânica aberta, na Carolina do Norte, EUA (ASHTON, MURRAY, ARNAULT, 2001; ASHTON; MURRAY, 2006a, 2006b; MURRAY; ASHTON, 2004).

Os esporões arenosos cuspidados encontrados no interior de corpos d’água restritos “*cusplate spits*” são análogos aos depósitos na Carolina do Norte (EUA), denominados “*cusplate forelands*”. Os estudos de McNinch e Wells (1999) no Cabo de *Lookout* (Carolina do Norte, EUA) indicam que os processos sedimentares permanecem ativos ao longo de toda a extensão submersa do depósito, e que este constitui-se em um sumidouro de longo prazo no balanço sedimentar da costa, na qual a célula litorânea a barlar “*updrift*” do cabo constitui-se na principal área fonte de sedimentos para o depósito submerso. Além disso, os autores também identificaram, por meio de uma detalhada compilação de dados batimétricos de longo prazo e análises estratigráficas, que a feição mantém a sua morfologia durante seu processo de desenvolvimento.

McNinch e Luetlich (2000) complementaram que os processos físicos responsáveis pela dinâmica sedimentar ao longo de toda a extensão do cabo envolvem uma atuação conjunta de correntes induzidas por ondas e correntes de maré, promovendo o contínuo aporte sedimentar para o depósito submerso, fator responsável pela manutenção da sua morfologia durante a transgressão marinha com o aumento relativo do nível do mar.

A partir de modelagem numérica e medições de correntes em campo ao longo do Cabo Lookout e associado extenso depósito arenoso submerso (Carolina do Norte, EUA), McNinch e Luetlich (2000) identificaram o desenvolvimento de correntes de maré residuais dirigidas para fora da costa. Os autores também argumentam que tais correntes em associação com os processos ondulatórios são responsáveis pela formação do banco “*Shoal*”, pela sua localização e pela sua manutenção de longo prazo.

O que é assumido adquirir maior importância nos estágios finais de desenvolvimento dos esporões, podendo diminuir ou mesmo cessar o seu desenvolvimento (ASHTON; MURRAY, 2006b).

Posteriormente, Park e Wells (2005) aplicaram o modelo parabólico de Refração-Difração (Ref/Dif 1) e análises de cartas batimétricas e fotografias aéreas para investigar os processos litorâneos sob uma ampla gama de condições de ondas no Cabo Lookout (EUA), identificando que os compartimentos costeiros na costa a barlar do Cabo (a “*updrift*” do depósito) constituem-se na principal fonte de sedimentos para o seu depósito submerso.

Isso é condizente com os estudos realizados em feições naturais, nas quais se observa a existência de uma conexão entre os segmentos costeiros a jusante “*downdrift*” e a montante “*updrift*” dos esporões (HÉQUETTE; RUZ, 1991; PARK; WELLS, 2005) e com os estudos numéricos para a análise esquemática de desenvolvimento dos esporões (ASHTON; NIENHUIS; ELLS, 2016). Héquette e Ruz (1991) e Park e Wells (2005), particularmente, destacam o papel desempenhado pela taxa de suprimento do setor costeiro a barlar do esporão. Héquette e Ruz (1991) demonstraram, inclusive, a partir de análises de correlação entre as taxas de retração costeira e do suprimento de sedimentos pela deriva litorânea, o forte controle que a disponibilidade de sedimentos exerce na migração do esporão em direção ao continente. Ashton, Nienhuis e Ells (2016) acrescentam, ainda, que, conforme o esporão se prolonga a partir da praia adjacente, a taxa de aporte sedimentar para o mesmo emerge através de mecanismos de retroalimentação “*feedback*” entre a sua raiz (porção proximal) e a sua terminação (porção distal), de modo que, em muitos casos, o acelerado crescimento (prolongamento) do esporão pode coincidir com reduzidas taxas de suprimento sedimentar – neste caso, evidências deposicionais podem ser decorrentes de fatores autogênicos.

Ou seja, a estabilidade do esporão reside, principalmente, em um frágil equilíbrio entre a disponibilidade de sedimentos (flutuações no suprimento de sedimentos) e o regime de ondas, conforme também é demonstrado nos estudos de Dan *et al.* (2011) e Allard *et al.* (2008).

Ademais, em uma situação de redução significativa no suprimento sedimentar, a canibalização⁴ do sedimento existente pode ocasionar o seu estreitamento e, inclusive, levar à ruptura da feição com relação à linha de costa (CARTER, 1988). De modo que, sob condições estáveis de variação relativa no nível do mar, os esporões podem se tornar desprovidos do volume de aporte sedimentar necessário para o seu contínuo desenvolvimento “*sediment-*

⁴ Canibalização: tendência de um sistema costeiro em que o suprimento de sedimentos pela deriva litorânea foi reduzido, de utilizar o sedimento praiado existente como fonte adicional para o subsequente transporte longitudinal de sedimentos (ORFORD, 2013).

starved”, uma vez que suas fontes são exauridas e, os mesmos tendem a evoluir em direção a uma forma em equilíbrio paralela às cristas de ondas incidentes “*swash-aligned*”, o que envolve a canibalização do sedimento existente e resulta em maiores mudanças morfológicas, modificando a sua forma em planta e perfil (CARTER, 1988; RANDAZZO; JACKON; COOPER, 2015).

No Brasil, Delaney (1965), Villwock (1984) e Toldo (1989, 1991, 1994) enquadraram a evolução do sistema lagunar da Lagoa dos Patos no quadro conceitual de Zenkovitch (1959) em razão de as características geomorfológicas da laguna suportarem o modelo de evolução lagunar, devido à concordância encontrada nas dimensões e formatos dos esporões existentes nas margens lagunares, e pela concordância entre o regime de ventos bimodal e a orientação do eixo lagunar principal. Os autores destacam, entretanto, a não ocorrência do processo de segmentação na Lagoa dos Patos devido à dimensão do corpo lagunar e à elevada contribuição hídrica da bacia de drenagem de sudeste, que impõe um fluxo natural a partir do Rio Guaíba até a sua desembocadura em Rio Grande, com o aumento do fluxo hídrico na extremidade livre dos esporões, impedindo o seu contínuo prolongamento no espaço e a segmentação lagunar.

Sumariamente, a formação e o desenvolvimento dos esporões estão principalmente vinculados (OTTMAN, 1967 *apud* DIEHL, 1997; ZENKOVITCH, 1959; ROSEN, 1972, 1975, 1982; ORFORD, 2004; RANDAZZO; JACKSON; ARNAULT, 2015; SCHWARTZ, 2005; DAVID-ARNOFF, 2010): 1. ao expressivo suprimento sedimentar; 2. aos regimes de ventos e ondas locais; 3. ao baixo gradiente da plataforma continental; 4. às flutuações relativas do nível do mar; 5. à baixa amplitude das marés; 6. à dominância dos processos sedimentares longitudinais; 7. à reduzida profundidade, uma vez que tais feições são originadas em águas rasas; 8. a influência da topografia costeira, como a presença de um ponto de apoio – hipótese que vem a ser posteriormente questionada por Ashton, Murray e Arnault (2001) e Ashton e Murray (2006a, 2006b), cujos resultados propõem que pequenas irregularidades podem criar “núcleos” para a formação de esporões rítmicos e; 8. a interferências humanas.

A gênese (origem) de tais feições é alvo de questionamentos e debates pela comunidade científica desde o século XIX e permanece até os dias atuais (GULLIVER, 1896; FISHER, 1955; PRICE; WILSON, 1956; ZENKOVITCH, 1959; WHITE, 1966; HOYT; HENRY 1971; ASHTON, MURRAY; ARNAULT, 2001; ASHTON; MURRAY, 2006a, 2006b; BORTOLIN, 2017) com argumentos intercambiando entre o modelo de Molde Forçante (estruturas organizadas espacialmente pela hidrodinâmica ou pelo embasamento geológico) e o Modelo de Auto-organização (estruturas emergentes de interações não lineares e processos de fortes alças

de retroalimentação “*feedback*” entre a hidrodinâmica e a morfologia através do transporte de sedimentos) – discussão que está fora do escopo da presente pesquisa de Tese. Contudo, apesar de ainda não existir um consenso a respeito da nucleogênese de feições rítmicas de larga-escala da linha de costa, o Modelo de Auto-organização é amplamente reconhecido pela comunidade científica pelo fornecimento de importantes esclarecimentos a respeito do comportamento morfodinâmico costeiro de larga-escala da feição.

2.1.3. Modelo de evolução de linhas de costas sujeitas ao mecanismo de instabilidade

Os resultados da modelagem exploratória do comportamento costeiro de larga escala realizada por Ashton *et al.* (2001) demonstraram que, ao contrário de estudos anteriores que assumiam que as ondas tendem a retilinizar o litoral (PELNARD-CONSIDERÉ, 1956; LARSON; HANSON; KRAUS, 1997), independentemente do ângulo de incidência de ondas em águas intermediárias (em profundidade abaixo da base da antepraia, referido pelo autor como “*deeper water wave angle*”), o poder difusivo das ondas (de retilinizar o litoral) decresce conforme o ângulo de incidência de ondas em uma profundidade abaixo da base da antepraia, aumenta em direção ao valor que maximiza o transporte sedimentar longitudinal ($\sim 45^\circ$) (ASHTON; MURRAY, 2006a).

Conforme destacado anteriormente, Zenkovitch (1959) e Rosen (1975) foram os primeiros pesquisadores a atestarem o comportamento instável de uma costa composta por material granular inconsolidado sujeita à incidência de ondas dominantes com elevada obliquidade. Posteriormente, Ashton, Murrau e Arnault (2001), Ashton e Murray (2006a, 2006b) e Murray e Ashton (2013) edificaram novos conceitos para a evolução de feições rítmicas de larga escala da linha de costa com a proposição do mecanismo de instabilidade – “*High-Angle Wave Instability Mechanism*” –, o qual opera com base na acoplagem entre a deriva litorânea e a morfologia costeira, sob a ação de ondas antidifusivas (ASHTON; MURRAY, 2006b). Por instabilidade, o autor refere-se à tendência no desenvolvimento ou na suavização de projeções na linha de costa ao longo do tempo; neste caso, a costa pode apresentar comportamento estável ou instável independentemente de estar erodindo ou crescendo ao longo do tempo.

A predição-chave é que sistemas costeiros com a presença de feições rítmicas de larga-escala da linha de costa, precisamente apresentam um clima de ondas antidifusivo (ASHTON; MURRAY, 2006b).

Sumariamente, os resultados do modelo de evolução da linha de costa “*Coastline Evolution Model*” (ASHTON; MURRAY, 2006a, 2006b) demonstraram que:

- (1) pequenas irregularidades na linha de costa podem tornar-se núcleos para a formação dos esporões;
- (2) a predominância de ondas antidifusivas “*high-angle waves*” resultam em instabilidades na linha de costa que podem ocasionar a emergência de feições costeiras com espaçamentos regulares e quase-periódicos através do processo de auto-organização;
- (3) a proporção de ondas antidifusivas determina a razão de aspecto (amplitude transversal versus espaçamento longitudinal) das feições emergentes da auto-organização da linha de costa;
- (4) quando a razão de aspecto (transversal/longitudinal) é significativa, zonas de sombra se estendem ao longo de cada projeção, e atuam como armadilhas para os sedimentos transportados através da crista. O efeito não-local do sombreamento de onda cresce conforme a feição cresce em amplitude, e alterações no grau de sombreamento de onda exercem influência de longa distância na estabilidade da costa adjacente (ELLS; MURRAY, 2012);
- (5) a distribuição angular das ondas incidentes afeta o formato do esporão, tal que padrões de crescimento e erosão do esporão são sensíveis a mudanças no clima de ondas;
- (6) para climas de ondas aproximadamente simétricos (ou seja, com reduzidas taxas de transporte sedimentar longitudinal líquido), o desenvolvimento da costa cuspidada exhibe um aumento relativo na amplitude transversal, estendendo-se em formato de ponta para o interior do corpo hídrico, conforme a proporção de ondas anti-difusivas é aumentada (ASHTON *et al.*, 2006a);
- (7) para clima de ondas assimétricos, as feições costeiras migram na direção da deriva litorânea líquida;
- (8) a dimensão da feição independe da magnitude da protuberância inicial na linha de costa, mas depende da proporção de ondas antidifusivas;
- (9) conforme o esporão cresce, o clima de ondas ao longo do seu flanco é modificado devido a ambos: o sombreamento de onda e a mudança na orientação da linha de costa; por consequência a maior parte da costa experimenta um clima de ondas estável (com baixos ângulos de incidência) apesar da instabilidade regional⁵, o que corrobora o observado

⁵ Instabilidade regional: ocorre quando a distribuição direcional das ondas resultantes (em águas profundas) constitui-se em duas componentes opostas, orientadas com ângulos oblíquos com respeito à costa.

na natureza nos Cabos da Carolina do Norte (EUA), que apresenta um clima de ondas local estável apesar do caráter instável do clima de ondas em águas profundas (ASHTON; MURRAY, 2006b).

Recentemente, a partir de uma série de experimentos laboratoriais controlados, Ashton, Nienhuis e Ells (2016) demonstraram o crescimento de esporões esquemáticos com diferentes formatos, e principalmente, orientações, sob a ação de um mesmo clima de ondas, sugerindo que a dinâmica no setor costeiro à barlar do esporão (através de mecanismos de retroalimentação entre a taxa de retração costeira, o clima de ondas e as taxas de aporte sedimentar), exerce maior controle no seu formato, na sua orientação e taxa de progradação.

Para o caso de lagunas alongadas, Ashton *et al.* (2009) propõem que um novo mecanismo de segmentação lagunar pode operar: a auto-organização da linha de costa, por meio da influência que os esporões cuspidados que atingiram aproximadamente a metade da largura da laguna exercem na pista de vento da laguna e, por sua vez, no campo de ondas incidentes na margem oposta e na deriva litorânea resultante, mecanismo referido pelo autor como “*fetch-limiting interactions*”. Esta dinâmica é demonstrada a partir da análise do fluxo longitudinal líquido e da estabilidade da linha de costa. Ou seja, os resultados de Ashton *et al.* (2009) indicam que, mesmo que os esporões não cresçam na posição diretamente oposta (defronte) no outro lado da margem lagunar, a feição é responsável pelo bloqueio das ondas no seu lado da laguna, de modo que a resultante assimetria no clima de ondas incidente no esporão da margem oposta é responsável pela sua migração ao longo da costa, em direção à feição responsável pela limitação na pista de vento, fazendo com os esporões atraiam-se mutualmente através do corpo lagunar independentemente do seu alinhamento, por fim acoplando-se e segmentando o corpo lagunar em menores lagos arredondados (Figura 6). E climas de ondas assimétricos resultam em lagos mais elípticos (ASHTON *et al.*, 2009), como é o caso das “células” da Lagoa dos Patos. A assimetria no clima de ondas incidente nas duas margens da laguna também condiz com os estudos de Toldo *et al.* (2006a) na Lagoa dos Patos, o qual observou predominante incidência de ondas de NE e ENE na margem oeste e dominante incidência de ondas de WSW na margem leste.

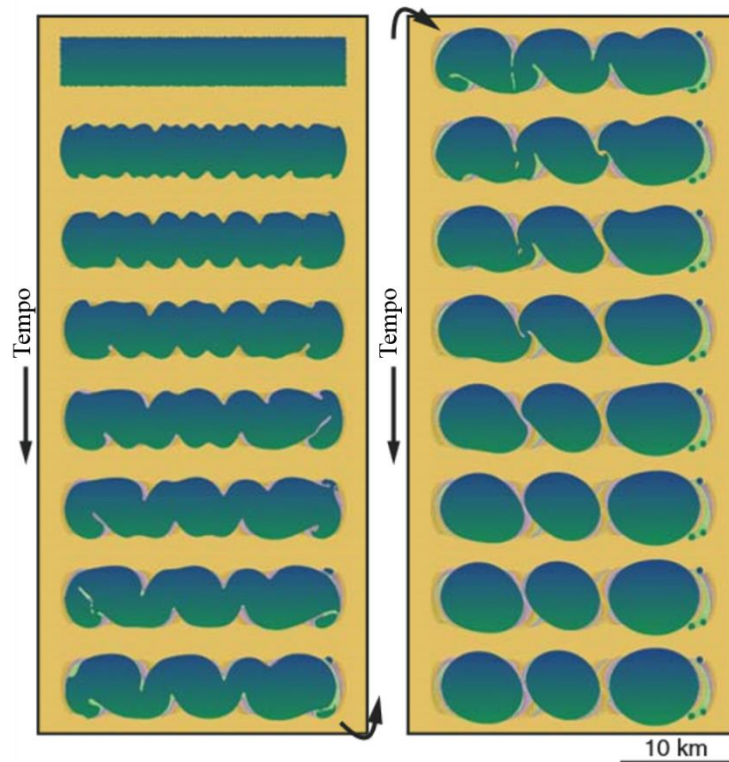


Figura 6. Resultados do modelo de evolução da linha de costa (CEM) adaptado para um corpo lagunar alongado, demonstrando o desenvolvimento das feições cuspidadas e a subsequente segmentação do corpo lagunar. Fonte: modificado de Ashton *et al.* (2009).

Cabe ressaltar, entretanto, que o modelo de Ashton *et al.* (2009) para a representação da formação de esporões cuspidados em uma laguna alongada e sua subsequente segmentação não leva em consideração a profundidade da bacia; a dissipação e a refração de ondas; e a formação de sub-áreas de geração de ondas locais. Além disto, também assume-se que a antepraia mantém um formato constante, diferente do observado ao longo dos arcos praias da Lagoa dos Patos.

Outro importante ponto a ser frisado é que a segmentação lagunar processa-se apenas em lagunas com baixa amplitude de maré (ROSEN, 1975), para a qual não drene uma expressiva contribuição hídrica (TOLDO, 1991), onde o regime energético seja suficiente para impedir a estabilização dos bancos com a colonização de vegetação e subsequente deposição de material lamoso, o que preveniria o transporte sedimentar induzido pela ação das ondas (ASHTON *et al.*, 2009) e com expressivas taxas de aporte sedimentar para os esporões.

Ressalta-se, também, que os trabalhos de Ashton, Murray e Arnault (2001), Ashton e Murray (2006a, 2006b), Ashton *et al.* (2009) e Murray e Ashton (2013) abordam um conjunto de processos longitudinais que operam, em particular, em escalas maiores que a largura da zona de surfe e, inclusive, da antepraia.

Este trabalho de Tese, por sua vez, fornece pela primeira vez a análise completa dos processos costeiros longitudinais de um sistema costeiro de uma costa cuspidada, desde a fonte (reentrância praial) até a terminação do esporão emerso e submerso em escala de evento à escala histórica, abrangendo em detalhe os processos longitudinais e as resultantes trocas sedimentares entre os compartimentos costeiros. ACESSA: 1. a análise da mobilidade da linha de costa em escala de evento (inter-anual) à escala histórica (décadas) a partir da utilização de dois métodos diferenciados para a quantificação das mudanças costeiras (DSAS e o Método do Polígono de Mudança), com o emprego de técnicas de geoprocessamento; 2. os controles que uma linha de costa cuspidada e sua associada morfologia submersa (em especial o extenso depósito de esporões arenosos) exercem na geração, propagação e atenuação de onda no interior de uma extensa (>10.000 km²) laguna alongada e; 3. os principais padrões de deriva litorânea potencial, propondo um modelo regional de balanço de sedimentos da costa e analisando sua influência no desenvolvimento dos esporões cuspidados, com o emprego de modelagem reducionista.

CAPÍTULO 3. SHORELINE EVOLUTION OF LAGOON SANDY SPITS AND ADJACENT BEACHES, LAGOA DOS PATOS, BRAZIL



Inaie Miranda <inaiemalheiros@gmail.com>

Your Submission to Journal of Coastal Research

The Journal of Coastal Research <em@editorialmanager.com>

28 de dezembro de 2018 00:05

Responder a: The Journal of Coastal Research <cmakowski@cerf-jcr.com>

Para: Inaie Malheiros Miranda <inaiemalheiros@gmail.com>

CC: cmakowski@cerf-jcr.com

Ref.: Ms. No. JCOASTRES-D-18-00092R1
Shoreline Evolution of Lagoon Sandy Spits and Adjacent Beaches, Lagoa dos Patos, Brazil.
Journal of Coastal Research

Dear Ms. Miranda,

This letter is to inform you that the revision of your manuscript was received in good condition. I have now completed my final adjudication of your contribution and am pleased to formally accept the paper for publication in the Journal of Coastal Research (JCR).

In due course you will receive page proofs, at which time it is highly recommended that you thoroughly check for errors. Please note that each author alteration (AA) will be assessed a \$5 USD revision charge. Printing errors are, of course, corrected free of charge.

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Take care and I thank you again for being a contributing author to the JCR. If you have any questions, please do not hesitate to contact us at cmakowski@cerf-jcr.com

With kind regards,

Chris Makowski, Ph.D.
Editor-in-Chief
Journal of Coastal Research (JCR)

Shoreline Evolution of Lagoon Sandy Spits and Adjacent Beaches, Lagoa dos Patos, Brazil.

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ABSTRACT

Miranda, I.M.; Toldo, E.E., Jr.; Klein, A.H.F., and Vieira da Silva, G., 2019. Shoreline evolution of lagoon sandy spits and adjacent beaches, Lagoa dos Patos, Brazil. *Journal of Coastal Research*, Florida, v. 35, n.5, 1010-1023. DOI: 10.2112/JCOASTRES-D-18-00092.1.

The development of lagoon sandy spits is dependent on sediment supply (mainly through longshore transport) and is often related to erosion of updrift beaches under high-angle waves. This paper provides an understanding of the short- to medium-term shoreline evolution of three symmetrical lagoon sandy spits and the related erosion of the adjacent bay beaches of Lagoa dos Patos, Brazil. To do so, two of the most widely used methods to quantify shoreline changes were applied: the transects-from-baseline method and the change polygon method. A historical analysis of the shoreline movement of approximately three decades (1984–2013), was carried out, aiming to track the source of sediments to the spits. Alternated phases of shoreline stability, deposition, and recession (less frequent) in short time intervals (years) showed correlation with the El Niño–Southern Oscillation and Southern Annular Mode indexes. Shoreline stability along beaches in the medium term (60.4% of Arambaré and 73.9% of Graxaim beaches, by the linear regression rate calculation), together with the very low average shoreline change rate of $+0.7 \text{ m y}^{-1}$ found using both methods, demonstrates that the sediment supply to the spits has been significantly reduced in the past three decades. Furthermore, the large-scale subaqueous portions of the spits are under wave-induced sedimentary reworking accompanied by the up-building of sandbanks from the submerged bars, followed by its landward migration and merging to the spit's shoreline. These results suggest that the spits of Lagoa dos Patos have their growth limited once the amount of sediment supply has been significantly reduced.

ADDITIONAL INDEX WORDS: Lagoon spit evolution, Landsat images, DSAS, change polygon method.

INTRODUCTION

The spits analyzed in this research correspond to nearly symmetrical morphological features in a simple cusped form, associated with large-scale submerged sandbars. They are attached at one end to the mainland and extend approximately half of the lagoon width to deeper water. These type of spits used to be classified as “cusped spits” a nomenclature first suggested by Shepard (1952) and adopted in the studies of Fisher (1955) in Koozata lagoon, St. Lawrence Island, Alaska; Zenkovitch (1959) in Chukchi Peninsula, Russia; Rosen (1975) in Nantucket Island, Massachusetts; and a posteriori by Ashton *et al.* (2009) in the planform coastline evolution model of sandy spits in fetch-limited elongated lagoon waterbodies. Rosen (1975, 90) differentiates (1) cusped spits from (2) cusped forelands as: (1) “a cusped projection of a beach into a body of water with fetch limited by basin shape, representing a reorientation of the shoreline to dominant wave-approach” and (2) “a cusped projection of a beach with no fetch limitations, representing reorientation of the shoreline to dominant wave-approach.” Previously, they also have been referred to as “V-bar” and “V-terrace” by Gilbert (1885).

These types of landforms correspond to accumulating cusped forms, developed in microtidal areas and generated by longshore processes as the result of waves approaching a shoreline at a high angle, and include beach cusps, beach protuberances, looped spits, cusped spits, and cusped forelands (Rosen, 1975). They are formed from a variety of materials of varying grain sizes, from fine sands to boulders (Randazzo, Jackson, and Cooper, 2015). The stability of spits is, very often, the result of a fragile equilibrium between the availability of sediments and the hydrodynamics, and because of the complex interactions between the processes shaping such geomorphologic features, the investigation is difficult and requires separate analyses for each of the processes (Dan *et al.*, 2011).

The continuous growth of spits is known to be closely related to the availability of sediment supply transported by longshore currents toward the spit ends (Ashton, Murray, and Arnault, 2001; Ashton, Nienhuis, and Ells, 2016; Bouchette *et al.*, 2014; Kraus, 1999; Kumar, Deepika, and Jayappa, 2013; Kumar, Narayana, and Jayappa, 2010; Petersen, Deigaard, and Fredsoe, 2008; Rosen, 1975; Uda, 2015; Zenkovitch, 1959). Following this well-accepted statement, the present study argues that the analyzed lagoon sandy spits have reached a development level characterized by a reduction in sediment supply from the erosion of associated beaches, thus limiting their growth. Therefore, the goal of this paper is to assess the shoreline evolution of spits and their adjoining beaches at an event to engineering scale, aiming

to investigate whether the expected low rates of shoreline retreat along the bay beaches are observed.

Study Area

Lagoa dos Patos is a very large and shallow barrier lagoon located at the coastal plain of Rio Grande do Sul state, in the southern Brazilian coast, with NE–SW orientation. It has length and width of about 240 and 40 km, respectively, and covers an area of approximately 10,000 km², with an average depth of almost 6 m and mean tidal amplitude of 0.45 m (Toldo, Almeida, and Corrêa, 2003). The geological evolution of the coastal plain of Rio Grande do Sul was controlled by Quaternary glacioeustatic sea level fluctuations responsible for the construction of four barrier lagoon depositional sequences, named from the youngest to the oldest as barrier lagoon systems I, II, III, and IV (Tomazelli, Dillenburg, and Villwock, 2004). System I is only exposed along the inner western shore of the lagoon and consists mostly of small, coalescing alluvial fans, whereas the long barrier that separates Lagoa dos Patos from the ocean is composite and includes both Pleistocene (system III) and Holocene (system IV) parts (Toldo *et al.*, 2000).

The weather of Rio Grande do Sul state is highly seasonal and strongly related to the large-scale pressure systems of the polar anticyclone in autumn and winter and the Atlantic anticyclone in summer and spring (Hasenack and Ferraro, 1989). The NE winds are dominant throughout the year, with southerly winds becoming more important during autumn and winter when the frontal systems are more frequent and the prevailing NE wind rotates to the southern quadrant (Moller *et al.*, 1996).

The lagoon receives fresh water from 170,000 km² of watershed, mostly from the Guaíba River at the Jacuí Delta at the NW end of the lagoon, with a much smaller contribution from the Camaquã River (Toldo *et al.*, 2000). In terms of sediment sources, Guaíba River contributes mainly mud to the lagoon because most of the sand is trapped at its large estuary (Toldo, Almeida, and Corrêa, 2003).

Lagoa dos Patos presents two distinct morphological and sedimentological bottom types: The first unit is composed predominantly of quartz sand and corresponds to the lagoon margin, where the spits are the most prominent features, extending approximately up to the 5-m isobath, and the second unit is composed predominantly of silty-clayey sediments and corresponds to a nearly flat lagoon bottom, from the ~5-m isobaths to deeper portions of the waterbody (Toldo, 1991; Toldo *et al.*, 2006). The emerged part of the sandy spits are marked by the border between the lagoon shoreline and the waterbody, and the submerged part of these

features extends into the lagoon as submerged bars, accompanying the bathymetric curve of 1 m below the water surface to a depth of 5–6m (Toldo, 1991).

This study is focused on the short- to medium-term shoreline evolution of three well-developed lagoon sandy spits (Dona Helena, Dona Maria, and Vitoriano) and two adjacent bay beaches, located on the central landward margin of Lagoa dos Patos (Figure 1). The subaqueous sandbars can reach lengths of about 20 km (Dona Maria spit), half of the lagoon width, being one of the longest spit features in lagoon waterbodies around the world. Similarly, Zenkovitch (1959) observed better development of “cusped spits” in the central region of some lagoon systems on the northern shores of Chukchi Peninsula, Russia.

The morphology of the lagoon is marked by many “cells” or “pools” limited by shallow sandy spits, and the lagoon is connected to the ocean through a narrow channel of 1–2 km width and 20 km length (Moller *et al.*, 1996).

Moller *et al.* (1996) showed that the tidal signal is of importance only near the exit to the ocean and is strongly attenuated as soon as it enters the Lagoa dos Patos inlet. Then, Fernandes *et al.* (2004) reinforced the previous studies, demonstrating that the single long and narrow inlet of Lagoa dos Patos acts as a natural hydraulic low-pass filter that reduces or eliminates tidal and subtidal effects inside the lagoon. Upstream, the main forcing effect controlling the dynamics of the system is generated by the local wind (Fernandes *et al.*, 2004).

As demonstrated by Moller *et al.* (1996, 2001), the wind drives circulation through its local and nonlocal effects. The former effect is associated with the longitudinal wind (NE/SW) to force the setup/setdown mechanism of oscillation (up to 1m) driving seaward/ landward flows during periods of low river contribution, in which the midlagoon region (the study area) constitutes the nodal zone, whereas the latter effect is observed by water level variations caused by the Ekman transport mechanism, which is an important factor in water exchange with the continental shelf (Moller *et al.*, 2001).

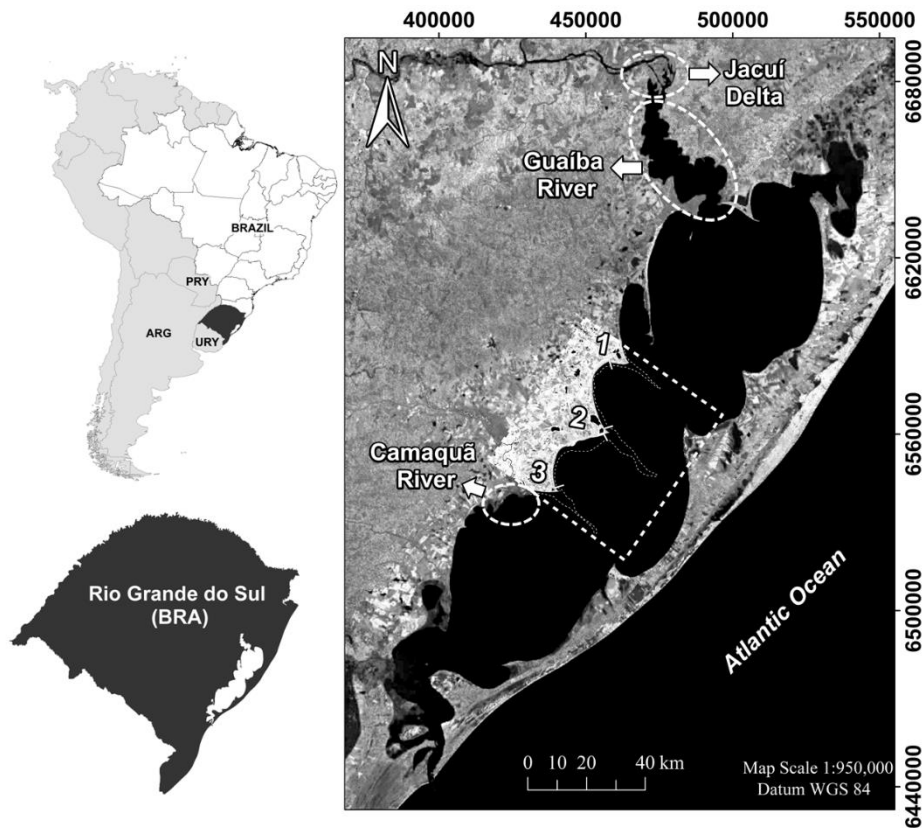


Figure 1. Study area covering the three analyzed lagoon sandy spits in the central landward margin of Lagoa dos Patos, indicated by (1) Dona Helena, (2) Dona Maria, and (3) Vitoriano, with the cross sections separating the spits from the bay beaches. The dashed contour lines indicate the 1-m below water surface isobathymetric line of the submerged spit bars and the dashed circles indicate the main tributaries of the system with their respective names. Image source: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, the National Centre for Space Studies (CNES)/Airbus DS, U.S. Department of Agriculture, U.S. Geological Survey, AeroGRID, IGN Spain, and the GIS User Community.

METHODS

Assessment of the short- and medium-term shoreline evolution was carried out by using the Landsat satellite images and two distinct approaches on the basis of a shoreline transect by the Digital Shoreline Analysis System (DSAS; Thieler *et al.*, 2009) and an area analysis by the change polygon method (CPM; Smith and Cromley, 2012). The steps performed in this research are summarized in Figure 2 and described below.

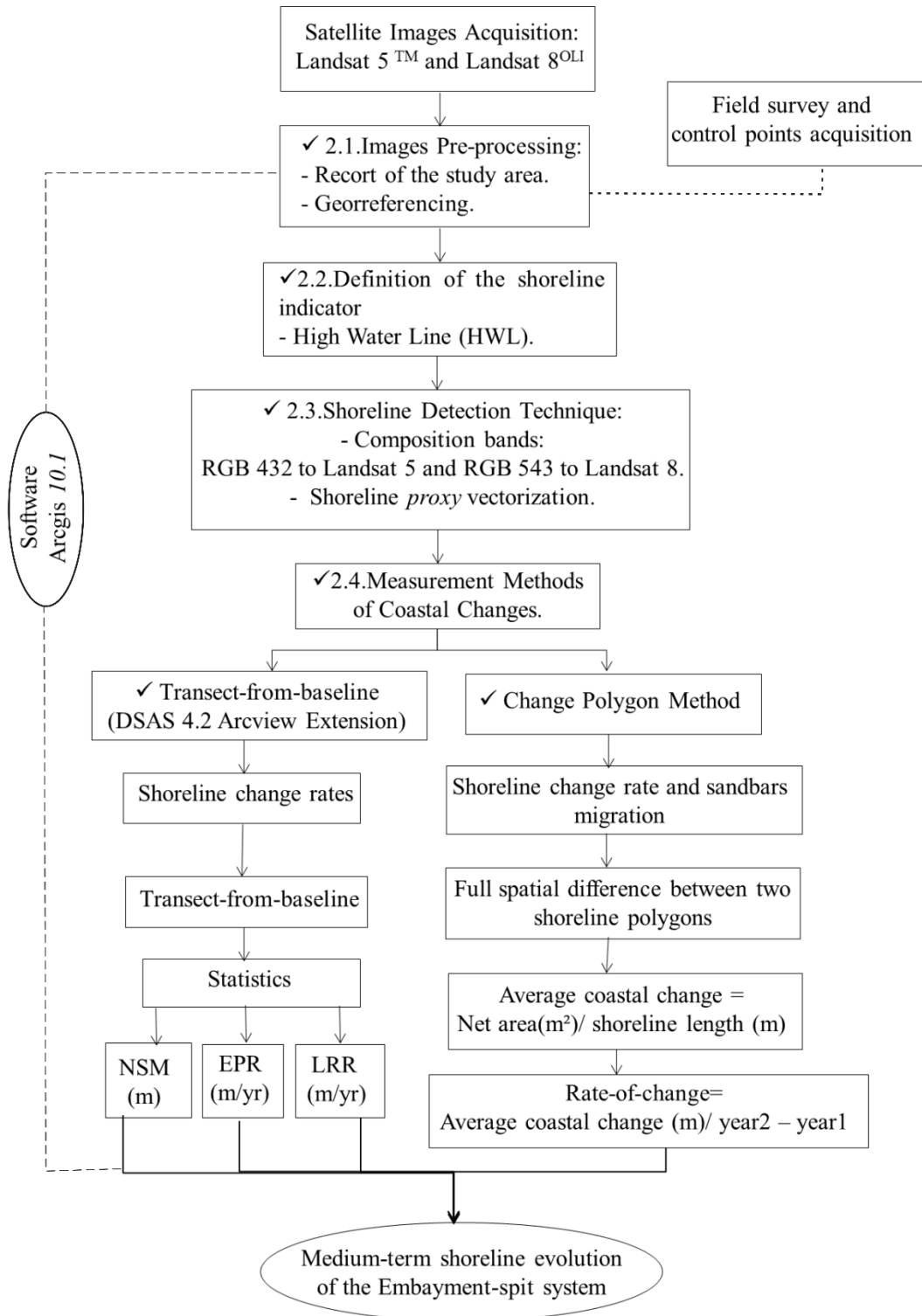


Figure 2. Flowchart showing the steps of the methodology used in this work.

Image Processing

Landsat images were selected because of their multispectral characteristics and large temporal and spatial coverage. Thus, they provided a consistent dataset with the longest time series available to access the shoreline changes of the study area. The images cover almost three

decades, including seven satellite images obtained by Landsat 5TM and Landsat 8 Operational Land Imager (OLI; Table 1) from the National Institute for Space Research of Brazil (INPE) and the U.S. Geological Survey. To correct the geometric distortion of the images, 33 ground control points were acquired with the differential GPS Outback Lite system, and image georeferencing was performed by ArcGIS 10.1 software. The respective errors were calculated by the root mean square error equation (Table 1).

To estimate the uncertainty of the shoreline change rate (U_t) the method proposed by Appeaning Addo, Jayson-Quashigah, and Kufogbe (2011) and Fletcher *et al.* (2012) was used. It assumes that the total uncertainty in the annualized shoreline change rate calculations is given by the square root of the sum of the squares of errors divided by the analyzed time period (Equation [1]):

$$U_{t(m/year)} = \pm \sqrt{\frac{E_{img1}^2 + \dots + E_{imgn}^2 + E_p^2}{T}} \quad (1)$$

where, E_{img1} , ..., E_{imgn} are the image rectification errors (Table 1), E_p is the pixel error (30 m), and T is the time period. Such an approach carries the assumption that the component errors are normally distributed (Appeaning Addo, Jayson-Quashigah, and Kufogbe, 2011; Appeaning Addo, Walkden, and Mills, 2008; Dar and Dar, 2009; Jonah *et al.*, 2016).

The uncertainty related to the tidal range was not taken into account because the tidal signal is insignificant at the study area (Kjerfve and Magil, 1989; Moller *et al.*, 1996; Fernandes *et al.*, 2004).

Table 1. LANDSAT satellite images dates, average water levels on the day of the images, details of images and respective acquisition dates and related errors.

| Acquisition Day | Water Level | Satellites | Sensors | Bands | Electromagnetic spectrum range (μm) | Spatial resolution (m) | RMSE (m) |
|-----------------|-------------|------------|---------------------------|---------------|--|------------------------|----------|
| 24/04/1984 | - | Landsat 5 | TM | 2 (Green) | 0.52 – 0.60 | 30 | 1.11 |
| 14/04/1988 | 0.51 | | (Thematic Mapper) | 3 (Red) | 0.63 – 0.69 | 30 | 1.75 |
| 07/04/1995 | 0.41 | | 4 (Near Infrared) | 0.76 – 0.90 | 30 | 1.18 | |
| 25/05/2001 | 0.84 | | | | | 0.82 | |
| 18/04/2005 | 0.44 | | | | | 0.93 | |
| 13/04/2009 | 0.56 | Landsat 8 | OLI | 3 (Green) | 0.525 – 0.600 | 30 | 1.14 |
| | | | (Operational Land Imager) | 4 (Red) | 0.630 – 0.680 | 30 | |
| 27/06/2013 | 0.37 | | 5 (Near Infrared) | 0.845 – 0.885 | 30 | 1.28 | |

Abbreviations: TM = Thematic Mapper, OLI = Operational Land Imager, RMSE = root mean square error.

Shoreline Indicator and Detection Technique Using Landsat Satellite Image

The proxy for the delimitation of the shoreline position in the present study was the high water line, proposed by Pajak and Leatherman (2002), because it was consistent along the entire analyzed perimeter and easily detected in the data source, satisfying the necessary criteria (Crowell, Leatherman, and Buckley, 1991; Gens, 2010; Pajak and Leatherman, 2002; Vieira da Silva *et al.*, 2016) for the delimitation of the shoreline position.

After various tests, it was found that the Landsat 5 red, green, blue (RGB) 432 composite and the corresponding 543 combination of Landsat 8 were best for delimiting the wet/dry boundary. By using these band combinations, the emerged sandy areas were easily identified by the color white because of the higher reflectance of the dry sand sediments in the visible region (0.4–0.7 μm) and near infrared (0.7–1.0 μm), whereas the sediments containing interstitial water had a clear bluegreenish color because of the different spectral response influenced by the target water. Similar spectral responses to suspended sediments and shallow waters was noticed by Alves, Amaro, and Vital (2003). This composite band also allowed the visualization of portions of the submerged sandbars and coastal vegetation (reeds), which were differentiated from the land by the increase in vegetation reflectance in the near infrared band (Landsat 5 TM band 4 and Landsat 8 OLI band 5).

Transect-from-Baseline

The analysis of shoreline changes was carried out through the transect-from-baseline method by using the DSAS 4.2 ArcGIS extension, developed by Thieler *et al.* (2009). To do so, 3301 shore-perpendicular transects were generated from a pre-established baseline, with a spacing distance of 25 m (covering 90.8 km), whereby the following statistics were computed: net shoreline movement (NSM), end point rate (EPR), and linear regression rate (LRR). A detailed description of the statistics can be found in Crowell, Douglas, and Leatherman (1997); Crowell, Leatherman, and Buckley (1991); Fenster, Dolan, and Elder (1993); Galgano and Douglas (2000); and Thieler *et al.* (2009).

The NSM and EPR were applied to six time spans (1984–1988, 1988–1995, 1995–2001, 2001–2005, 2005–2009, and 2009–2013) to investigate the existence of cyclical trends through the measurement of coastal changes (Equations [2] and [3]). The LRR was used for the medium-term shoreline assessment, taking into account all available shoreline vectors:

$$\text{Average NSM} = \frac{\sum \text{NSM}}{n^\circ \text{ transect}} \quad (2)$$

$$\text{Annual rate of change} = \frac{\text{Average NSM}}{\text{Time (years)}} \quad (3)$$

Change Polygon Method (Smith and Cromley, 2012)

The CPM, developed by Smith and Cromley (2012), uses two different shorelines to construct a polygon topology based on the geometric assumption that area = length x width. To do so, the shoreline vectors were converted to the polygon format and the subtraction between these two shoreline polygons resulted in a series of simple polygons representing: accretional areas, where the recent shoreline transposes the limits of the oldest shoreline; recessional areas, where the oldest shoreline transposes the boundary of the youngest shoreline; and without change or null, when the intersection between the polygons fell into the same area (Smith and Cromley, 2012). The sub-polygons were then decomposed into positive (depositional) and negative (recessional) areas and summed to produce a total change estimate (A_f , net area). The net area was then divided by one of the shoreline perimeters (P), resulting in an average coastal change (Equation [4]) (Smith and Cromley, 2012):

$$D = \frac{A_f(m^2)}{P(m)} \quad (4)$$

The estimation of the net annual rate of change was then given by the ratio of the average coastal change (D) and the time period between the two coastlines.

RESULTS

The results are described by short- and medium-term shoreline change assessments according to the aforementioned methodologies.

Short-Term Shoreline Evolution (End Point Rate)

Stability, depositional, and, less frequently, recessional trends were observed in short time intervals (years) (Figures 3 and 4). The uncertainty error estimation for the shoreline change rates in the short-term analysis ranged from ± 4.3 up to ± 7.5 m y^{-1} .

From 1984 to 1988 the bay beach shorelines were mainly stable, in which 93% of Arambaré and 88.2% of Graxaim were within the uncertainty error (± 7.5 m y^{-1}). Furthermore, 3.8% of Arambaré and 5.3% of Graxaim shorelines experienced recession rates ranging from -7.5 to -10 m y^{-1} , mainly at the northern coast of the embayment. The highest retreat rates were observed at the south margin of Dona Helena spit (-18.2 m y^{-1}) and at the distal end of Vitoriano

spit (-30.2 m y^{-1}) (Figure 3a). The former is not an indication of erosion but the change in direction of the distal end. Also, high depositional rates occurred next to the inlet of Velhaco River ($+16.0 \text{ m y}^{-1}$) and at the inlets of irrigation channels 3 ($+27.7 \text{ m y}^{-1}$) and 4 ($+19.1 \text{ m y}^{-1}$), whereas the southern margin of inlet 5 retreated with rates ranging from -10.0 up to -14.9 m y^{-1} .

From 1988 to 1995, Arambaré bay beach showed the predominant occurrence of shoreline progression (51.0%), ranging from $+4.3$ to $+7.5 \text{ m y}^{-1}$, followed by 37.2% stable values ($\pm 4.3 \text{ m y}^{-1}$), whereas 59.4% of Graxaim bay beach was stable, followed by 31.3% prograding shoreline on the north central sector of the embayment, ranging from $+4.3$ to $+7.5 \text{ m y}^{-1}$. Moreover, very high depositional rates were observed at inlets 4 ($+20.0 \text{ m y}^{-1}$) and 5 ($+17.9 \text{ m y}^{-1}$), along with the prolongation of Dona Maria ($+18.4 \text{ m y}^{-1}$) and Dona Helena ($+11.3 \text{ m y}^{-1}$) spits (Figure 3b). Despite the general trend of shoreline progradation during this time-period, the updrift coast of Vitoriano spit ($\sim 3 \text{ km}$) retreated with rates of -4.3 m y^{-1} to -6.6 m y^{-1} , while its distal end prograded at $+13.7 \text{ m y}^{-1}$. At the same time, the migration of an adjacent sandbank could be observed.

From 1995 to 2001, 77.8% and 90.8% of Arambaré and Graxaim shorelines, respectively, were stable ($\pm 5.0 \text{ m y}^{-1}$), followed by 19.3% of Arambaré coastline experiencing retreat rates ranging from -5.0 to -7.5 m y^{-1} , predominantly on the southern coast of the embayment, whereas, on the northern extremity of the beach 0.76% shoreline progradation was observed (Figure 3c). Graxaim bay beach presented a smaller percentage of shoreline recession (6.7%), with rates ranging from -5.0 to -7.5 m y^{-1} , predominantly occurring at the inflection point of the shoreline (in the surroundings of inlet 5). Also, punctual depositional values occurred at the mouths of inlets 4 ($+10.9 \text{ m y}^{-1}$) and 5 ($+5.13$ to $+6.6 \text{ m y}^{-1}$) (Figure 3c). Maximum shoreline retreat rates of -29.3 m y^{-1} were observed at the distal edge of Dona Maria spit, while the distal edge of Vitoriano spit showed a high depositional rate ($+12.8 \text{ m y}^{-1}$) (Figure 3c). The high depositional rate of the former is due to the merging of the adjacent sandbank.

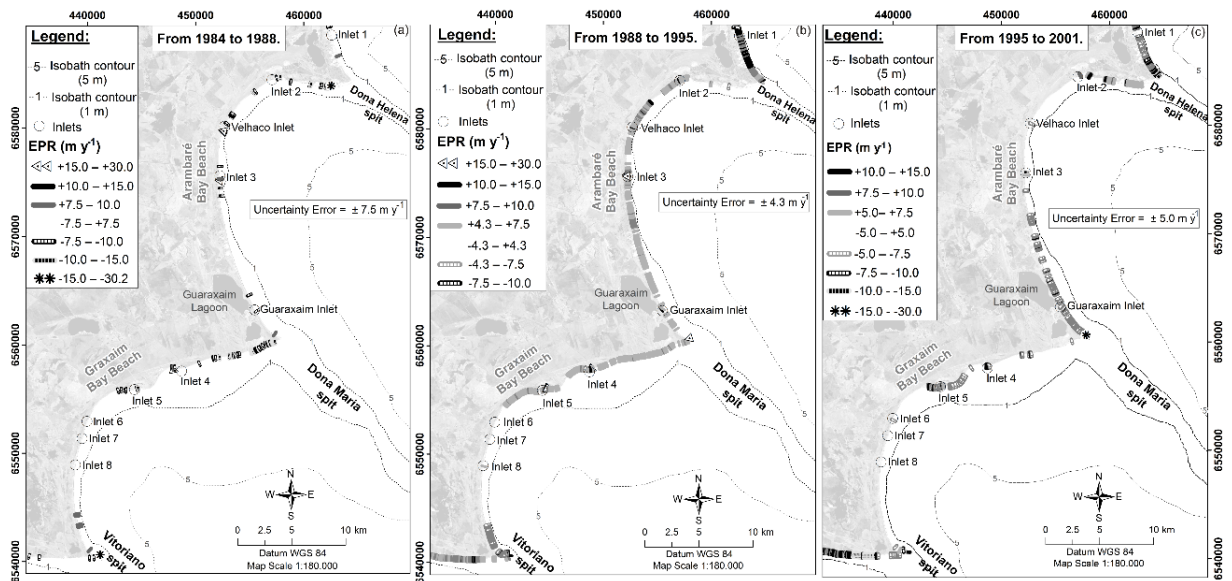


Figure 3. Shoreline change rates using the EPR statistic for time intervals (a) 1984–1988, (b) 1988–1995, and (c) 1995–2001. Image source: Landsat 5. (Ver versão colorida da figura no apêndice-A).

Between 2001 and 2005, 87.3% and 44.0% of Graxaim and Arambaré beaches, respectively, showed a stable trend ($\pm 7.5 \text{ m y}^{-1}$). Shoreline progradation was observed 55.9%, mainly along the central and southern coast of Arambaré, ranging from $+7.5 \text{ m y}^{-1}$ up to a peak of $+20.1 \text{ m y}^{-1}$ next to inlet 3 (Figure 4a). Graxaim bay beach, on the other hand, experienced less shoreline progradation, with 12.6% of the coastline and rates ranging from $+7.5 \text{ m y}^{-1}$ up to a peak of $+17.2 \text{ m y}^{-1}$ next to inlet 4. The recurved Vitoriano spit migrated landward (-21.1 m y^{-1}) and elongated northward (mainly) and southward. Also, a very high progradation rate of $+48.9 \text{ m y}^{-1}$ was observed at the southern edge of this spit. The northern spit (Dona Helena) also showed a high progradation rate at its eastern edge, $+19.9 \text{ m y}^{-1}$, and the Dona Maria spit showed a retreat rate of -17.8 m y^{-1} because of the southward migration of its distal end toward the approaching sandbank.

Another period marked by the predominant shoreline stability trend was between 2005 and 2009, corresponding to 94.7% of Arambaré and 89.2% of Graxaim ($\pm 7.5 \text{ m y}^{-1}$). Moreover, 4.3% and 7.9% of Arambaré and Graxaim, respectively, experienced recession rates ranging from -7.5 to -10 m y^{-1} . The landward migration of Vitoriano spit (-12.7 m y^{-1}) continued during this time span, together with sediment deposition at its southern edge, with rates of $+25.6$ and $+38.7 \text{ m y}^{-1}$. The east edge of Dona Maria spit was marked by a very high deposition rate of $+59.4 \text{ m y}^{-1}$ because of the merging of the adjacent sandbank (Figure 4b). Representative sediment input from the sandbar to the shoreline was also experienced by Vitoriano spit between 1995 and 2001. Moreover, localized high depositional rates were observed at the east

margin of Lagoa do Graxaim inlet ($+12.4 \text{ m y}^{-1}$) and $+20.5 \text{ m y}^{-1}$ and $+24.0 \text{ m y}^{-1}$ next to inlet 4.

The dominant trend to general stability continued during the time interval from 2009 to 2013, during which 80.9% of Arambaré and 89.5% of Graxaim were stable. However, a considerable occurrence of shoreline retreat (15.7%), ranging from -7.5 to -10.0 m y^{-1} along the southern coast of the Arambaré, was observed, whereas the northern extremity of the embayment (south margin of Dona Helena spit) was marked by depositional values ranging from $+7.5 \text{ m y}^{-1}$ up to a maximum of $+30.1 \text{ m y}^{-1}$ at the accentuated shoreline curvature (Figure 4c). Moreover, a high retreat rate of -19.6 m y^{-1} was observed at the left margin of Lagoa do Graxaim inlet. The distal end of Dona Helena spit retreated (-25.4 m y^{-1}), as well as the distal end of Dona Maria spit (-57.5 m y^{-1}). Sediment accumulation continued occurring at the southern edge of Vitoriano spit, but with lower rates, ranging from $+8.7 \text{ m y}^{-1}$ up to a maximum of $+22.1 \text{ m y}^{-1}$.

Graxaim embayment was marked by depositional rates of 8.8%, ranging from $+7.5$ to $+10.0 \text{ m y}^{-1}$, mainly concentrated along the southern part of the beach, with peak values at inlet 7 ranging from $+10.1$ up to $+11.5 \text{ m y}^{-1}$ and at inlet 5 of $+13.0 \text{ m y}^{-1}$ (Figure 4c).

Overall, the bay beaches showed the prevailing occurrence of stable values. However, alongshore variability with intercalated periods of recession and deposition were observed in short time intervals (years), and the very high values of shoreline progradation and retreat were localized and mainly situated at the mouths of the irrigation channels and at the spit ends, demonstrating its accentuated dynamic.

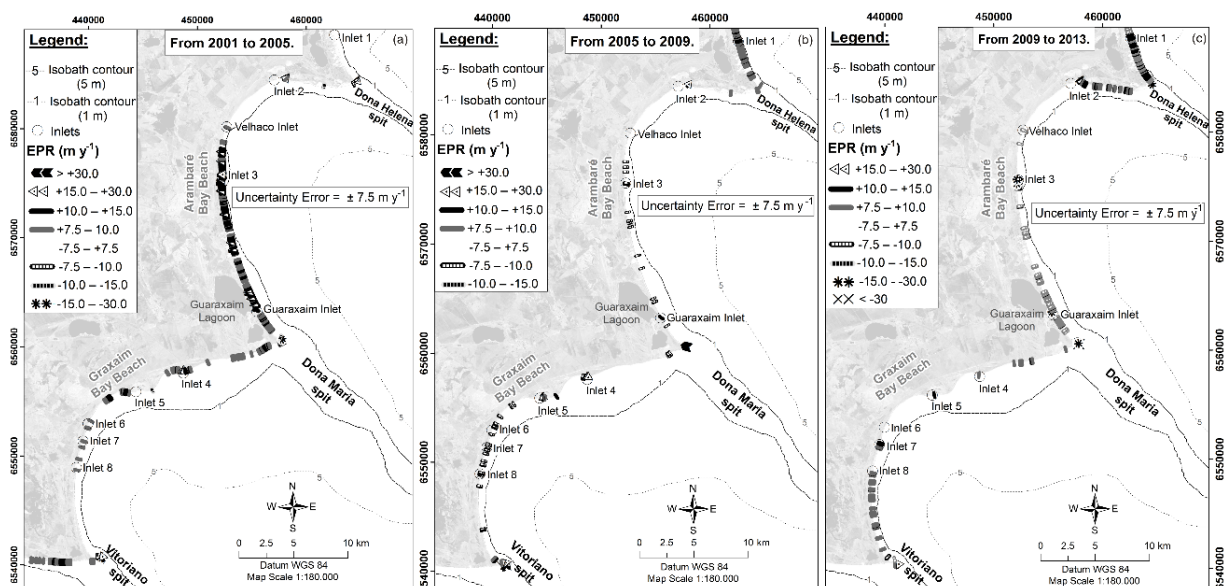


Figure 4. Shoreline change rates using the EPR statistic for time intervals (a) 2001–2005, (b) 2005–2009, and (c) 2009–2013. Image source: Landsat 5. (Ver versão colorida da figura no apêndice-B)

Change Polygon Method

The rates of shoreline movement provided by the CPM were very similar to the rates from the EPR method (Table 2).

Table 2. Comparative annual rates (m yr^{-1}) of shoreline changes using the transect-from-baseline (DSAS) and Change Polygon Methods.

| Time interval | Transect-from-baseline (m yr^{-1}) | Change Polygon Method (m yr^{-1}) |
|---------------|--|---|
| 1984-1988 | -1.54 | -1.50 |
| 1988-1995 | +3.89 | +3.93 |
| 1995-2001 | -2.21 | -2.16 |
| 2001-2005 | +4.32 | +4.34 |
| 2005-2009 | -0.75 | -0.60 |
| 2009-2013 | -0.21 | -0.46 |
| 1984-2013 | +0.729 | +0.734 |

From 1984 to 2013, the CPM showed a mean shoreline movement of $+0.7 \text{ m yr}^{-1}$, within the annualized long-term error of $\pm 1.5 \text{ m yr}^{-1}$, which can characterize the maintenance of the sedimentary balance along the three analyzed decades.

In the last three decades, Vitoriano spit had undergone significant morphological changes. Therefore, this spit was selected to exemplify the morphological behavior of these coastal features along the central landward margin of Lagoa dos Patos lagoon during this time (Figure 5).

During the analyzed time period, sandbanks were observed emerging from the subaqueous sandbars with a tendency to landward migration. From 1984 to 1988, the proximal and the outermost sandbanks lost 39.9 and 7.8 km^2 of area, respectively (Figure 5a). In the subsequent time span (1988–1995), the updrift coast of Vitoriano spit retreated while the distal end of the spit prolonged toward the approaching sandbank (Figure 5b). Between 1995 and 2001, the larger and nearest sandbank joined the emerged spit, changing its shape and morphology and resulting in a high sand accumulation of 21.5 km^2 of area at the eastern edge of the emerged spit, associated with a northern sandbank with an area of 45.8 km^2 (Figure 5c). From 2001 to 2005, higher sand accumulation was observed (82.6 km^2), and the Vitoriano spit acquired a recurved shape and showed onshore migration. Moreover, another two sandbanks (29.0 and 4.1 km^2) were built up from the submerged sandbar (Figure 5d). Between 2005 and 2009, the onshore migration of the current recurved spit continued, together with the elongation of its northern end and the obstruction of sediment at its southern distal edge (30.5 km^2) (Figure 5e). From 2009 to 2013, the high sediment accumulation in the southern edge of the spit

continued, whereas the north “hook” lost an area of 48.4 km², which was deposited as a shoal (Figure 5f).

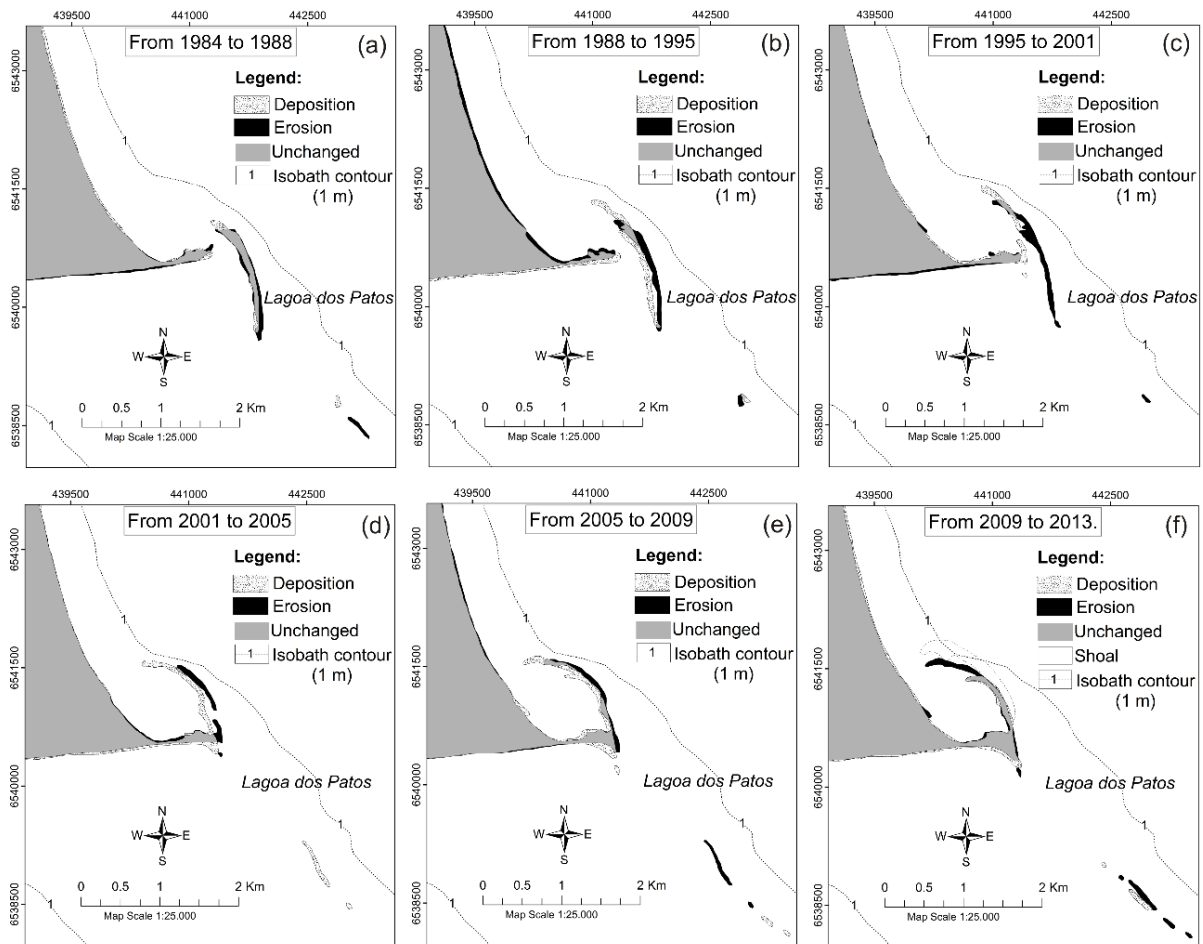


Figure 5. Analysis of the recent geomorphological evolution of the Vitoriano spit, highlighting the sedimentary reworking (cannibalism) of the submerged feature, through the up-building process of sandbanks from the large-scale submerged sandbars, followed by its landward migration and merging to the spit’s shoreline during (a) 1984–1988, (b) 1988–1995, (c) 1995–2001, (d) 2001–2005, (e) 2005–2009, and (f) 2009–2013.

Moreover, the growth of new beach ridges was also observed (Figure 6). The sandbank buildup process and subsequent landward migration over the submerged bars of the sandy spits, eroding and accreting while migrating and merging into the spit’s shoreline, were also observed for the others two spits (Appendices A and B).

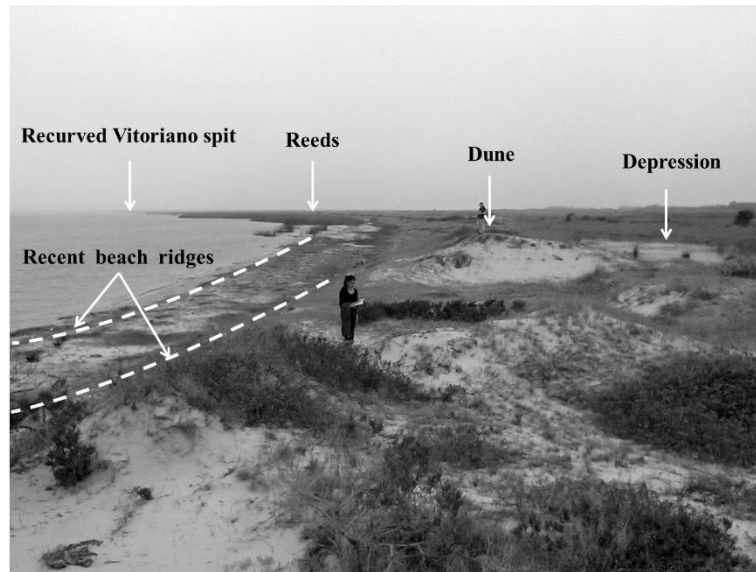


Figure 6. Growth of recent beach ridges at the sheltered updrift coast of the Vitoriano spit.

Medium-Term Shoreline Assessment (EPR and LRR)

From 1984 to 2013, the EPR statistic depicted stable values (within the uncertainty error of $\pm 1.5 \text{ m y}^{-1}$), accounting for 84.3% of Arambaré and 78.3% of Graxaim coastlines. Less frequent low progradation rates (from $+1.5$ to $+3.0 \text{ m y}^{-1}$) along the northern half part of the bay beaches were observed, accounting for 14.2% of Arambaré and 18.7% of Graxaim (Figure 7a). However, the LRR statistic depicted a higher occurrence of low progradation rates (Figure 7b), especially for the Arambaré coastline, which showed 37.6% low progradation rates ($+1.5$ to $+3.0 \text{ m y}^{-1}$) and 60.4% stability. Graxaim continued presenting the dominant behavior of shoreline stability (73.9%), with 20.9% low depositional rates.

On Arambaré, moderate shoreline progradation, ranging from $+3.0$ to $+4.4 \text{ m y}^{-1}$, was observed at the Velhaco mouth and inlets 2 and 3, up to a maximum of $+6.2 \text{ m y}^{-1}$ at the accentuated curvature of shoreline between the northern embayment and southern margin of Dona Helena spit (Figure 7b.1). Retreat rates were observed in the right margin of Lagoa do Graxaim inlet (ranging from -1.7 to -2.5 m y^{-1} for the EPR statistic and from -1.9 to -2.8 m y^{-1} for LRR), whereas a deposition rate of $+2.4 \text{ m y}^{-1}$ was observed by LRR at its northern margin, showing the southward migration of the inlet. Furthermore, low to moderate retreat rates, ranging from -1.7 up to -4.6 m y^{-1} , were observed at the northern distal end of Dona Maria spit by both applied statistics (Figure 7b.2). On Graxaim, moderate shoreline progradation ranging from $+3.0$ to 6.0 m y^{-1} (2.4 % by EPR and 2.9 % by LRR) were observed at inlet 5 and along the shoreline indentations close to inlets 4 and 5. The LRR analysis indicates shoreline retreat at the extreme south of Graxaim bay beach in the attachment sector with Vitoriano spit, ranging from -1.6 to -1.8 m y^{-1} , which accounts for 1.6% of Graxaim shoreline. Accentuated and

localized high depositional values (ranging from +6.0 to +9.5 m y⁻¹) were observed at the mouth of inlet 4. Moderate to high progradation rates, from +3.4 up to +14.6 m y⁻¹, were observed at the distal end of Vitoriano spit (Figure 7b.3). Overall, no representative retreat rates were observed in the medium-term shoreline assessment of the bay beaches.

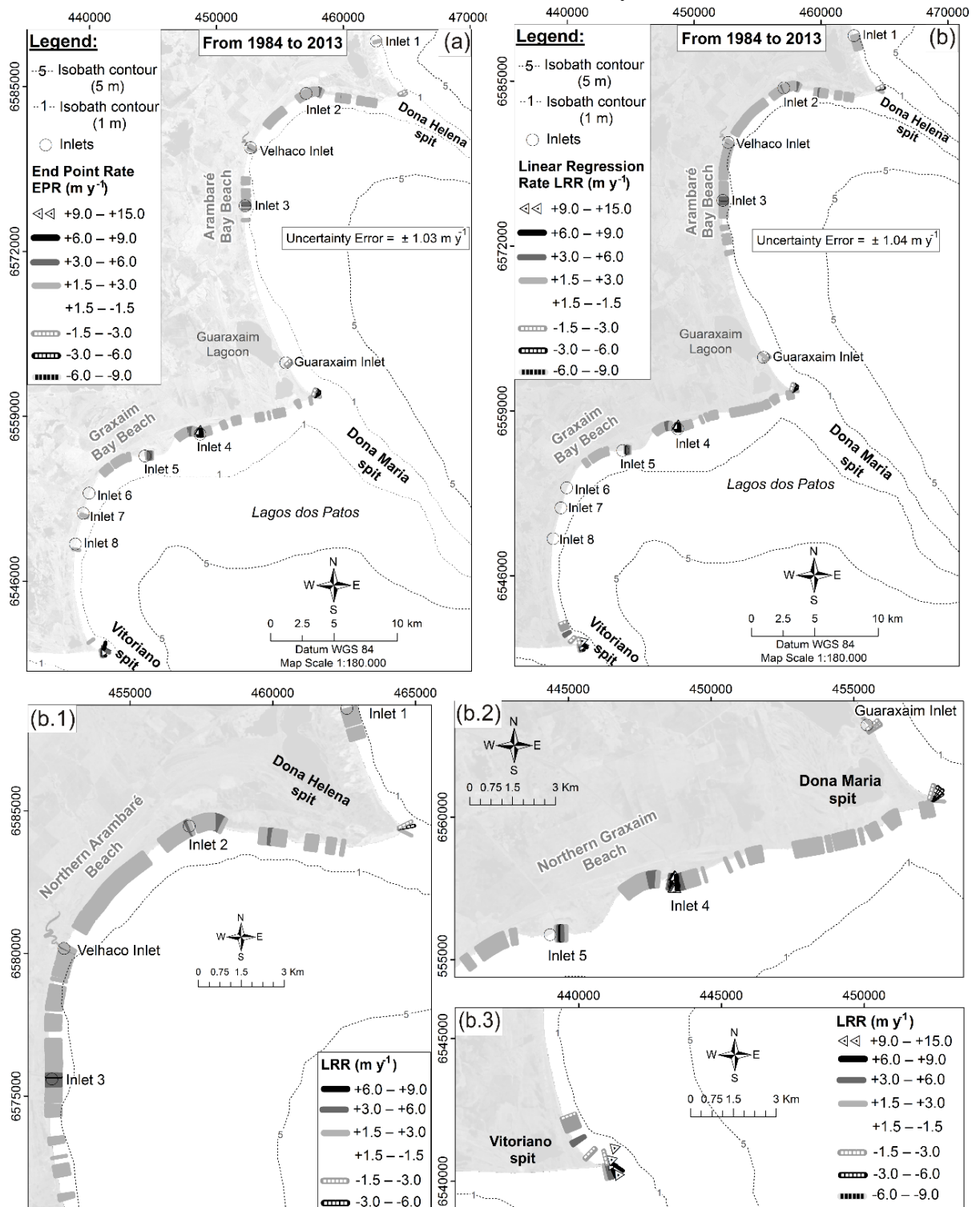


Figure 7. Annual rate of shoreline change for the medium-term analysis using: (a) EPR and (b) LRR statistics, with magnified portions of the northern Arambaré beach (b.1), the northern coast of Graxaim (b.2), and the coastline of Vitoriano spit (b.3). Image source: Landsat 5. (Versão colorida da figura no apêndice-C)

DISCUSSION

Satellite remote sensing data has been widely used for automatic or semiautomatic coastline identification. In particular, much work exploited Landsat TM data by applying different analysis techniques (Guariglia *et al.*, 2006). Limitations, such as the relatively coarse spatial resolution (30m), are mitigated by their synoptic, multitemporal, and multispectral information (Cenci *et al.*, 2013; Niya *et al.*, 2013). For the present work, the spectral characteristics of the Landsat satellite images allowed the use of near-infrared, blue, and green RGB composite bands to delimit the wet/dry land boundary with more confidence and replicability. The use of Landsat satellite images to measure and spatially analyze the coastal changes over a period of decades has been a common practice over the last decades (Alves, Amaro, and Vital, 2003; Appeaning Addo, Jayson-Quashigah, and Kufogbe, 2011; Cenci *et al.*, 2013; Ghanavati *et al.*, 2008; Gisp, 2014; Kumar, Deepika, and Jayappa, 2013; Kumar, Narayana, and Jayappa, 2010; Niya *et al.*, 2013; Noernberg and Marone, 2003; White and El Asmar, 1999; Yang and Ouchi, 2010).

The transect-from-baseline method has been used by many researchers and agencies as the standard method to determine long-term coastal change rates and coastal hazard zones (Crowell, Leatherman, and Buckley, 1991). On the other hand, Smith and Cromley (2012) suggested that the polygon technique may be a more robust method, being less invariant to parameter changes. The main drawbacks and advantages pointed out by Thieler *et al.* (2009), Smith and Cromley (2012), Albuquerque *et al.* (2013), and this study are summarized in Table 3.

For the present research, the use of two different methods has proven to be complementary. The transect-based method allowed better control of shoreline movement of the bay beaches, and CPM allowed the complete measurement of area changes of the spits and associated sandbanks. Furthermore, for the transect-based method, no large differences were observed between the range (maximum and minimum rates) of the EPR and LRR results. However, the LRR algorithm identified a larger stretch of prograding shoreline because of the increased amount of shoreline data considered.

Table 3. Advantages and disadvantages of the statistics applied by the transect-from-baseline (DSAS) vs the change polygon method.

| Methods | Advantages | Disadvantages |
|--|---|---|
| Transect-from-baseline (DSAS) | Use of robust and widely acceptable shoreline change statistics (Thieler <i>et al.</i> , 2009) | Large lengths of the shoreline may be omitted in the measurement processes (Smith and Cromley, 2012). |
| | Include all shoreline data available in the final computation by the LRR statistic. | The average change rate bring residues from regions which are not reached by the transects (Albuquerque <i>et al.</i> , 2013) <u>Solution:</u> Higher spatial resolution between transects. |
| | Automatic and local assessment of the shoreline movement. | The choice of a proper baseline (Smith and Cromley, 2012). |
| | Provide a better control and monitoring of local coastal changes by densely distributed shore-parallel transects | Transects can intersect each other and do not reach the nearest shoreline (Smith and Cromley, 2012). <u>Solution:</u> Depending on the coastal indentation, transects needs to be carefully checked. |
| Change Polygon Method (Smith and Cromley, 2012) | Area analysis (Smith and Cromley, 2012) | Low localized control on the monitoring of the shoreline change rates. |
| | Allows the quantification of morphological changes in which it is not possible to use the same baseline of reference, e.g.: sandbanks migration and recurved spit (in m ²). | Sensitive to the definition of the shoreline length used as denominator in the measurement of the net change area (Smith and Cromley, 2012). |
| | | Does not account for more than two shoreline vectors in the annual rate of change. |

Medium-Term and Short-Term Shoreline Assessments

When analyzing short-term shoreline variability, a dominant stability trend (>80%) of the bay beaches was observed from 1984 to 1988, from 2005 to 2009, and from 2009 to 2013. These periods were coincident with neutral Southern Annular Mode phases and greater correlation with the precipitation patterns over the central region of the Rio Grande do Sul coastal plain, including Lagoa dos Patos. Furthermore, during these periods, a weak El Niño (2009) and moderate (2010–2011) and weak (2012) La Niña years occurred, which resulted in low-precipitation anomalies (Schossler *et al.*, 2018). Allied to this, discharge values below the average were registered during the La Niña period (Vaz, Moller, and Almeida, 2006). This

scenario, in turn, resulted in a prevalence of steady hydrodynamic conditions over the lagoon margins.

From 1988 to 1995, a representative shoreline progradation was observed, accounting for 51% of the Arambaré coastline and 31.3% of Graxaim, with depositional rates mainly concentrated on its northern sector. On the other hand, the southern extremity (the updrift coast of Vitoriano spit) retreated along with the prolongation of the distal end of Vitoriano spit ($+13.7 \text{ m y}^{-1}$) toward the sheltered area of the approaching sandbank (Figure 3b). Ashton, Nienhuis, and Ells (2016, p. 193) highlighted that the rate of sediment input to the spit itself emerges through feedback with the downdrift spit end, so that “faster spit progradation may coincide with reduced sediment input to the spit itself.” In this case, this process may be locally intensified by changes in the wave diffraction-refraction patterns promoted by the adjacent sandbar.

In the subsequent time span (1995–2001) the adjacent sandbank migrated onshore, reducing area and joining to Vitoriano spit (Figure 5c), which resulted in a high progradation rate of the spit ($+12.8 \text{ m y}^{-1}$) (Figure 3c). Besides the predominant occurrence of shoreline stability during this period (77.8% of Arambaré beach and 90.8% of Graxaim embayment), Arambaré experienced significant shoreline retraction (21.4%) in the southern half of its coast (Figure 3c). This period was marked by a peak in precipitation anomalies, concomitant with a very strong El Niño phase from 1997 to 1998 (Schossler *et al.*, 2018) and intense hydrodynamic conditions from an increased freshwater discharge at the top of the lagoon (Fernandes *et al.*, 2002). Together with the occurrence of 20 registered cases of storm surges on the adjacent coast associated with extratropical cyclones, from 1997 to 1999, and winds from the SE, SW, and SSW directions and speeds of 16 to 24 m s^{-1} (Saraiva, Bedran, and Carneiro, 2003). This scenario may have contributed to higher wind waves in the lagoon and the consequent erosion pattern observed in the downcoast sector of Arambaré bay beach, transporting sediment northward.

The following time interval (2001–2005) was a period of overall depositional trend, with 55.9% of shoreline progradation in the center and the southern part of Arambaré bay beach, along with a smaller percentage of progradation rate values at Graxaim embayment (12.5%), mainly along irregularities of the shoreline next to inlets 4 and 5 and near the southern margin of Dona Maria spit (Figure 4a). In contrast with the previous time interval, this suggests an interannual exchange of sediments between the beach extremities.

Medium-term analyses of shoreline trend demonstrate that Arambaré and Graxaim beaches remained relatively stable. The EPR analysis showed the predominant stability for both bay beaches, and the LRR depicted greater extension of the shoreline (9.47 km) with low progradation rates (Figure 7). The absence of representative retreat rates throughout the bay beaches (the main source of sediments) shows the limited sediment supply to the continuous growth of the spits, once it is assumed that embayment erosion from the accentuated littoral drift resulting from the dominant approach of oblique wave angles is the main process responsible for the growth of the spit features. Therefore, the analyzed bay beaches are under a stabilization process while the submerged bars of the spits are sediment starved, leading to the cannibalization of proximal regions of the sandbars, accompanied by the up-building of sandbanks. Once emerged, landward migration of the sandbanks over the submerged sandbars was observed, ending with a merging with the mainland (Figure 5). The case of Vitoriano spit resulted in the development of a recurved shape that trapped the littoral drift from the northern and southern margins of the spit and resulted in the growth of incipient beach ridges on the northern shore (Figure 6). These beach ridges likely were built by the net longshore transport to the south on the west embayments, as observed by Toldo *et al.* (2006), who relate the net longshore transport with the wind-wave action generated by the predominant NE winds during summer and spring.

Moreover, the landward migration of the recurved Vitoriano spit highlights the importance of the cross-shore transport effects, despite the longshore sediment transport being the dominant component of the lagoon embayment–spit system.

CONCLUSIONS

The two methods applied to quantify and analyze shoreline changes (transect-from-baseline and CPM) are found not to be exclusionary, but complementary. The overall annual rates of shoreline change were very similar by both methods. The transect-from-baseline method provided robust results with regard to the local behavior of shoreline movement by using equally spaced transects and including all the coastline vectors available in the longest period of shoreline change measurement (by LRR statistic), which allowed the detailed analyses of shoreline behavior for Arambaré and Graxaim bay beaches.

The CPM presented better results for analyzing the up-build process of sandbanks and their landward migration along the submerged bars. Although Landsat images are not particularly recommended for quantifying shoreline change rates in short time periods, the results presented here allowed the interannual analysis of beach variabilities associated with the

cyclogenesis of local climatic aspects, in which the neutral Southern Annular Mode phases associated with weak El Niño and weak and moderate La Niña years were coincident with the predominant stable behavior of the coastline, whereas a higher occurrence of shoreline retraction was observed during very strong El Niño periods. A better control in regard to the frequency and direction of storm winds and related hydrodynamic conditions in the lagoon waterbody (e.g., wave energy distribution) is recommended in the literature to further explain the spatial variability of shoreline recession and progradation trends because of the variable orientation of the shoreline.

In the medium term, from 1984 to 2013, the two analyzed beaches did not show representative recessional rates by either statistic (EPR or LRR). Additionally, the average change rate of approximately $+0.7 \text{ m y}^{-1}$ (which is within the uncertainty error of $\pm 1.5 \text{ m y}^{-1}$) found by both methods (transect-from-baseline and CPM) reinforce that no erosional trends were observed in the longest period. Therefore, the lagoon sandy spits in the central west margin of Lagoa dos Patos are growth-limited by a reduced sediment supply from the adjacent beaches, and the submerged bars have been providing sediment to the emerged spit coastline during the last three decades.

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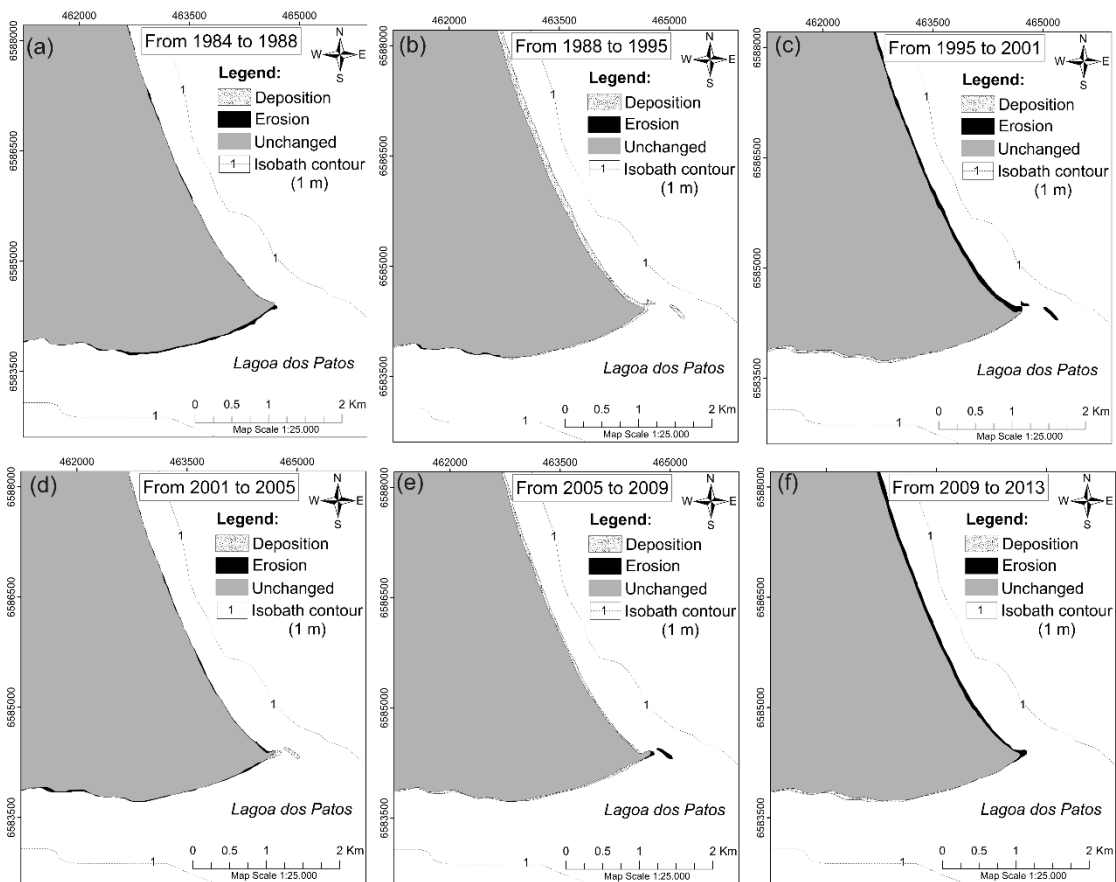
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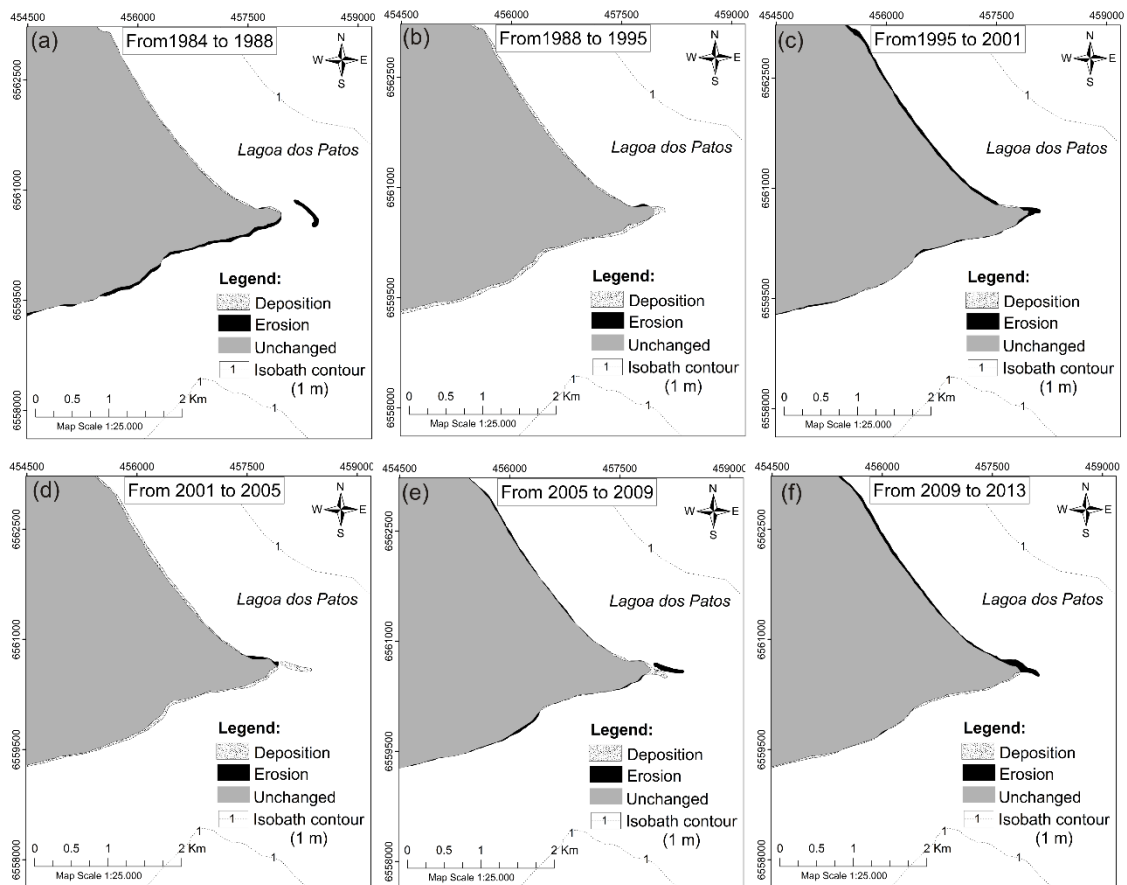
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APPENDIX A. Study case of the decadal coastal morphological evolution of Dona Helena spit, showing sandbar up-building, followed by landward migration and merging to the spit shorelines: (a) 1984–1988, erosion of the south margin of Dona Helena spit; (b) 1988–1995, up-building of two sandbanks of 4435.4 m² and 11,369.8 m² next to the edge of Dona Helena spit; (c) 1995–2001, erosion of the sandbank and the northern coast of the spit; (d) 2001–2005, approach of the sandbank observed in 1995; (e) 2005–2009, merging of the sandbank to the spit’s shoreline; (f) 2009–2013, erosion of the distal end and the northern coast of the spit again.



APPENDIX B. Study case of the decadal morphological evolution of Dona Maria spit into six time spans from 1984 to 2013, emphasizing the general trend of sandbar upbuilding and subsequent shoreward migration and merging to the spit shoreline: (a) 1984–1998, erosion in the adjacent 28,200-m² sandbar ; (b) 1988–1995, welding of the eroded sandbank observed in the previous time span; (c) 1995–2001, erosion of the distal end and the northern coast of the spit; (d) 2001–2005, emergence and approach of another 25,264.9-m² sandbank; (e) 2005–2009, joining of the sandbank to the spit shoreline and up-building of another 6734.3-m² sandbank; (f) 2009–2013, erosion of the distal end and the northern coast.



CAPÍTULO 4. THE ROLE OF CUSPATE SPITS ON WAVE ATTENUATION AND ENERGY REDISTRIBUTION IN A COASTAL LAGOON, LAGOA DOS PATOS, BRAZIL



Inaiê Miranda <miranda.inaie@gmail.com>

GMLE: Your manuscript entitled The Role of Cuspate Spits on Wave Attenuation and Energy Redistribution in a Coastal Lagoon, Lagoa dos Patos, Brazil.

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Ref.: Ms. No. GMLE-D-19-00113R1

The Role of Cuspate Spits on Wave Attenuation and Energy Redistribution in a Coastal Lagoon, Lagoa dos Patos, Brazil.

Geo-Marine Letters

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With kind regards,

Gabriele Uenzelmann-Neben, Ph.D.
Editor-in-Chief of Geo-Marine Letters

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The Role of Cuspate Spits on Wave Attenuation and Energy Redistribution in a Coastal Lagoon, Lagoa dos Patos, Brazil

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ABSTRACT

This research uses a process-based model (Delft3D), validated with measured wave data, to investigate the controls that a cusped shoreline and its associated submerged morphology have on wave generation, propagation and attenuation within a large elongated lagoon (Lagoa dos Patos, Brazil). A method based on the Energy-Flux-Method was applied to the historical wind dataset to define representative wind cases to be used as forcing conditions in the model. The results show that, during extreme wind conditions, the spits dissipate wave energy in the lagoon. This (wave attenuation and the wave sheltering effect) controls the stability of the adjacent coastline. The wave attenuation varies between 18 and 46% along the submerged spit depending on the crest width and the amplitude of the incident waves. Waves are mainly attenuated in the proximal and central portions of the spits where the spits are wider, resulting in a reduced transmitted energy to the adjacent coastline, while larger waves are also attenuated on the distal end of the spits. The degree of attenuation depends on the direction of wave generation, the respective fetch, the spit width, and the water depth. A strong relationship of mutual co-adjustment between the morphology and the wave field results in a very low occurrence of oblique wave angles of incidence, especially for waves propagating across the long lagoon axis. Furthermore, the wave attenuation over the spits is also responsible for its progressive erosion, which from decades to centuries, may lead to an increase of changes on the lagoon shorelines.

KEYWORDS: Delft 3D, wave dissipation, wave energy gradients, wave propagation, wave shadow, cusped shorelines, fetch-limited.

INTRODUCTION

Understanding changes in the wave characteristics of the nearshore zone is an issue of fundamental importance because it drives sediment transport that will produce morphological changes, which in turn alters the fluid dynamics, restarting the cycle which drives the coastal evolution (Cowell and Thom, 1994).

The temporal behavior of the coastal systems varies according to the directionality of the wave climate, which can vary globally because of changes in the wind climate induced by climate change, or locally, because of changes in the wave transformation processes controlled by the nearshore bathymetry (López-Ruiz *et al.*, 2014; 2015). Therefore, a better understanding of coastal processes in the nearshore zone can increase our capacity to predict coastal changes at different time scales, increasing the potential to assist in the enhancement of coastal community resilience and the management of natural resources.

Researchers and coastal managers have shown an increased interest in predicting the shoreline behavior at larger time and spatial scales (Ells and Murray, 2012; Nicholls *et al.*, 2013). However, there is still a demand for improved prediction of change which occurs locally (French *et al.*, 2016) to better inform the decision making of coastal planning and/or protection measures. In this sense, this research has the main focus of better understanding local processes occurring along the central west margin of Lagoa dos Patos (Brazil), where a touristic beach is located (Arambaré) (Figure 1).

The lagoon settings constitute a good opportunity to investigate the wave dynamics in a fetch-limited complex coastal system. The studied region is a typically elongated lagoon, with very large dimensions ($> 10,000 \text{ km}^2$) constricted into four main “cells” by three large-scale cusped spits extending underwater below 1m depth until approximately the center axis of the lagoon. High energy wind-waves can be generated in the lagoon, wherein a maximum of 1.6 m and 4.8 s of wave height and period was predicted by Toldo *et al.* (2003) under a windstorm of 25 m/s from the WNW direction.

The coastal morphology of lagoons resemble the coastal morphology of the ocean shore as many processes found on lakes and lagoon shores are similar to those found on the ocean shore (Carter, 1988). Physical features become more comparable with increasing dimensions of the water body and smaller tidal range (Aronow, 1982). In this sense, this work investigates the controls of the lagoon cusped shoreline (orientation) and the associated submerged morphology (in particular the submerged cusped spits and the morphological transition zone of the shoreface width) on the alongshore distribution of the incident wave characteristics,

including the analysis of different directions of waves generated by representative wind cases, propagation patterns and the wave attenuation by the spits.

Significant advances were achieved in the understanding of the wave input forcing on the large-scale coastal behavior of cusped shorelines (Ashton and Murray, 2006a, b). However, the influence of nearshore processes, such as the modification of incident wave directions is not well understood (Thornton *et al.*, 2000), especially in coastal environments dominated by locally generated, fetch-limited, young seas.

Spits are among the most dynamic coastal landforms on the Earth Surface, whose development is primarily controlled by the sediment supply (Héquette and Ruz, 1991; Park and Wells, 2007), and by the characteristics of the incident wave conditions. Cusped spits are a type of spit that develops within fetch-limited water bodies (ex.: elongated lagoons or marginal seas), in which fetch-limiting controls result in a prevailing occurrence of oblique wave-approach angles at the beginning of the rectilinear shore (Zenkovitch, 1959; Rosen, 1975; Toldo, 1991; Toldo *et al.*, 2003).

A rectilinear shore composed by unconsolidated sediments is an unstable shape under a dominant oblique wave incidence to the shore. As a result, the shoreline is reoriented in accordance to the dominant wave-approach directions due to strong gradients on the longshore sediment transport, which leads to the formation of cusped shoreline features (Zenkovitch, 1959; Rosen, 1975; Ashton *et al.*, 2001). Finally, when those features reach a finite-amplitude, they start to interact with each other by the wave-sheltering effect, resulting in the self-organization of the coast driven by strong feedbacks between the longshore sediment transport and the morphology (Ashton *et al.*, 2001; Ashton and Murray 2006a, b).

A long-term requirement for a fetch-limited environment to achieve an equilibrium shape is that energy needs to be efficiently spread along the shore (Carter, 1993). By absorbing and adjusting to environmental changes, the shoreline increases its potential to become a buffer against fluctuations in ambient energy, especially during storm events (Carter and Woodrofe, 1994). In the case of an elongated lagoon composed by unconsolidated material, paired cusped spits develop (Zenkovitch, 1959; Rosen, 1975; Carter, 1993).

Spits are recognized by their importance in providing natural coastal protection from the direct wave attack to nearby beaches (FitzGerald and Buynevich, 2009; Allard *et al.*, 2008). Cusped spits, in particular, have a far-field response in the stabilization of its leeward coast due to the wave sheltering effect (Ells and Murray, 2012) which controls the sediment transport

patterns and thus erosion-prone areas. Moreover, this work demonstrates the buffering effect of the emerged and submerged cusped spits during high wave energy events in the lagoon.

Several studies have reported on the relationship between the spits and the wave regime (Ashton and Murray, 2006b; Park and Wells, 2007; Allard *et al.*, 2008; López-Ruiz *et al.*, 2012; Escudero *et al.*, 2019). Ashton and Murray (2006b) have shown how the angular distribution of the incident waves affects the long-term development of cusped spits, as; 1) the major proportion of anti-diffusive waves (oblique wave incidence below the toe of the shoreface) increases the amplitude growth of the cusped features, and that 2) the degree of asymmetry of the wave regime are preponderant parameters for the shape and forms of evolution of the cusped features. Allard *et al.* (2008) showed that variations in sand accumulation on spits, at seasonal to interannual time-scales, are the result of variations in the longshore sediment transport modulated mainly by wave height. Petersen *et al.* (2008) has found that the radius of curvature of spits varies according to the height of the incoming waves. López-Ruiz *et al.* (2012) study on a schematic “flying spit” showed that different combinations of significant wave height, period and angle of incidence (the determinant parameter) produces different surfzone widths. Thus, evidencing the high control in the alongshore distribution of incident wave angles and heights on the morphodynamics of coasts with spits.

In this sense, this research assesses the influence of spits on the wave height attenuation and on the incident wave characteristics [energy (W/m) and angle of incidence ($\phi-\theta$)] entering the nearshore region of the lagoon bay beaches, considering different directions of wind-wave generation. Despite wave attenuation studies receiving more attention by the scientific community since the 1990's, with an increased number of published studies since 2012 (Scopus searching for “wave attenuation” and refined to “swell” and “wind-wave”) in different types of environments, this is the first time that the impact of spits on wave attenuation within a lagoon water body has been assessed. In this context, this work is guided by the following research questions:

- 1 To what degree do the large-scale cusped submerged features act on the wave attenuation, considering extreme wave fields from different directions in the fetch-limited water body of Lagoa dos Patos, Brazil?
- 2 How does the control of the coastline orientation and submerged relief of the lagoon margin (where the cusped spits constitute the most important features) act on the incident wave characteristics in the nearshore region of the associated lagoon beaches?

This paper first contextualizes the analyzed lagoon system and the local environmental conditions in the regional setting section, followed by the methodology steps for the selection of representative wind cases used as forcing conditions for the lagoon wave model. The model calibration and validation procedures, and the measurements of the alongshore wave energy and attenuation were then described. Next, the wave attenuation by the spits and the alongshore distribution of the wave energy and angles of incidence are presented in the results section. The results are followed by a discussion on the controls of the variability of wave attenuation along the spits and the implication for the adjacent coastline, the alongshore distribution of wave-approach angles ($\varphi-\theta$) and energy (W/m) in the nearshore region of a cusped coast in its final stages of development. Finally, we present the main conclusions of the research.

REGIONAL SETTING

The coastal plain of Rio Grande do Sul is composed by four barrier-lagoon systems, formed during four transgressive-regressive events associated with four sea-level highstands, where the Patos-Mirim Lagoon Complex is the dominant feature (Tomazelli *et al.*, 2000).

The regional climate (see Figure 1 for location) is marked by the influence of the Atlantic anticyclonic wind circulation which leads to the dominant northeasterly (5 m s^{-1} mean velocity) wind action throughout the year, followed by southwesterly and southerly winds (8 m s^{-1} mean velocity) during the passage of cold fronts, most frequent during winter and autumn (Delaney, 1965; Stech and Lorenzetti, 1992; Tomazelli, 1993; Klein, 2012). It has a total mean annual precipitation of 1200-15000 mm, which may strongly vary from year to year and is principally related to the path and frequency of cold front passages (Nobre *et al.*, 1986).

Strong El Niño phases were also correlated with an increased precipitation pattern over the drainage basin of the state (Schooler *et al.*, 2018), resulting in an increase of the discharge of the main lagoon tributary - Guaíba river (Vaz *et al.*, 2006). The resultant increase in the lagoon water level (Fernandez *et al.*, 2002) allied to an increased frequency of cold front passages (Saraiva *et al.*, 2003) resulted in an increased shoreline retraction over the study area within a short-time period, from 1997-1999, in spite of the medium-term tendency coastal stability (Miranda *et al.*, 2019).

Local Wind Climate

The analysis of the wind dataset is in accordance to previous studies of the wind regime of the region (Klein, 2012). Where, higher occurrence of winds from the NE direction are

observed, with magnitudes between 5.5 and 8.0 m/s, classified as a moderate breeze (Beaufort 5) (Table 1). Furthermore, there is a considerable occurrence of wind speeds ranging from 8.0 to 10.8 m/s (12.4%) corresponding to Beaufort 6. Wind from the NE direction dominates the frequency of occurrence (14.1%), followed by the ENE (10.2%), E (7.6%), S (6.8) and SSW (6.2%) directions. Wind speeds between 10.8 to 13.9 m/s occur mainly from the NE, S and SSW directions and near gale cases (Beaufort 8) occur mainly from the S, followed by the E and ESE, NE and SSW directions.

Table 1. Joint occurrence of wind speed (m/s) and directions with the number of hours per class. The darker shades of gray indicate classes with higher frequency of occurrence.

| Beaufort Scale | Speed \ Dir. | N | NNE | NE | ENE | E | ESE | SE | SSE | S | SSW | SW | WSW | W | WNW | NW | NNW | Freq. (%) |
|----------------|--------------|------|------|-------|-------|------|------|------|------|------|------|------|------|------|------|------|------|-----------|
| 1 | 0.0-0.3 | 8 | 4 | 9 | 9 | 7 | 6 | 9 | 2 | 4 | 8 | 6 | 6 | 13 | 10 | 6 | 11 | 0.2% |
| 2 | 0.3-1.5 | 178 | 220 | 183 | 128 | 130 | 125 | 123 | 122 | 131 | 109 | 156 | 182 | 194 | 176 | 168 | 183 | 3.4% |
| 3 | 1.5-3.3 | 1230 | 1517 | 1060 | 730 | 804 | 689 | 676 | 592 | 658 | 501 | 812 | 1058 | 1010 | 953 | 969 | 1078 | 19.5% |
| 4 | 3.3-5.5 | 779 | 1703 | 2704 | 2334 | 1881 | 1376 | 1350 | 1178 | 1516 | 1293 | 1368 | 1235 | 743 | 594 | 846 | 968 | 29.7% |
| 5 | 5.5- 8.0 | 176 | 901 | 3847 | 2749 | 1826 | 1163 | 1038 | 1043 | 1624 | 1565 | 1050 | 963 | 465 | 197 | 268 | 326 | 26.1% |
| 6 | 8.0-10.8 | 27 | 227 | 2255 | 1411 | 786 | 522 | 464 | 383 | 815 | 915 | 304 | 566 | 250 | 110 | 44 | 36 | 12.4% |
| 7 | 10.8-13.9 | 13 | 22 | 285 | 137 | 115 | 98 | 132 | 95 | 190 | 143 | 22 | 89 | 52 | 47 | 23 | 19 | 2.0% |
| 8 | 13.9-17.2 | 2 | 14 | 22 | 7 | 31 | 27 | 16 | 16 | 33 | 19 | 12 | 7 | 10 | 22 | 6 | 4 | 0.3% |
| 9 | 17.2-20.7 | 6 | 4 | 8 | 2 | 2 | 4 | 2 | 3 | 4 | 6 | 6 | 5 | 2 | 7 | 1 | 2 | 0.1% |
| | Freq. (%) | 3.3% | 6.3% | 14.1% | 10.2% | 7.6% | 5.4% | 5.2% | 4.7% | 6.8% | 6.2% | 5.1% | 5.6% | 3.7% | 2.9% | 3.2% | 3.6% | |

Lagoa dos Patos

The lagoon water body covers a surface area of approximately 10,000 km² (Toldo *et al.*, 2006b), it is 240 km long, the largest width reaches 59.8 km, and it has an average depth of 6 m (Toldo, 1991).

A succession of broad bays and sandy spits occur on the lagoon margins as a result of the wave action and related littoral currents which tend to orient the beaches at right angles to the direction of the prevailing waves (Delaney, 1965; Villwock, 1984; Toldo *et al.*, 2003). Despite the wave power being inferior when compared to an open ocean beach, the lagoon shoreface is considered an energetic environment for a lagoon, with an annual mean wave-power incident on the west margin of 2,057 kW/m-1 and 1,046 kW/m-1 on the east margin, and despite the east side receiving less energy than the west side, the storm condition is typical for the east side (Toldo *et al.*, 2003).

The lagoon beaches associated with the spits fulfill the definition of bay beaches proposed by Nordstrom (2005), in which locally generated waves and wave-induced currents are the main factors affecting the bay beach morphodynamics. This is despite wind-induced and

tidal currents which may also play a role in morphological changes. For the case of Lagoa dos Patos, the inlet acts as a dynamic low-pass filter that eliminates tidal and subtidal effects inside the lagoon water body (Moller *et al.*, 1996; Fernandes *et al.*, 2004).

Also, the two main longitudinal components of the winds exert an important control on the set-up/set-down oscillation mechanism, for instance, during low discharge, the NE wind cause a decrease in the lagoon water level on the north region and an increase in the south, facilitating the leak-flow towards the sea, as opposed the the SW wind, while the central lagoon water body constitutes the nodal zone (Moller *et al.*, 1996).

Based on 21 years of measured data, from 1985 to 2006, Andrade Neto *et al.* (2012) found an average discharge value from the main contributor of the Guaíba river to be 988 m³/year, with a maximum discharge of 5,246 m³/s.

The west lagoon margin is marked by the presence of six lagoon sandy spits (Toldo, 1991), among which, the three symmetrical rhythmic features on the central landward margin, and the associated northern (Arambaré) and southern bay beaches, are the focus of this research (Figure 1). Table 2 depicts the details of the morphological characteristics of the analyzed spits.

In addition, Miranda *et al.* (2019) indicated that the west lagoon spits are experiencing a phase of limited sediment supply, such that no representative shoreline recession rates were found along the lagoon bay beaches (the source of sediments to the spits) in the medium-term assessment of shoreline changes; i.e. the shorelines showed an average change rate of ± 0.7 m y⁻¹ (within the uncertainty error). In an inter-annual period, in turn, the bay beaches showed alternateing phases of stability, deposition, and recession (albeit less frequent) trends (Miranda *et al.*, 2019). The authors also highlighted the need for studies regarding the frequency and direction of storm wind conditions and the resultant wave regime and sediment transport patterns along the lagoon coast to better understand and predict possible morphological changes.

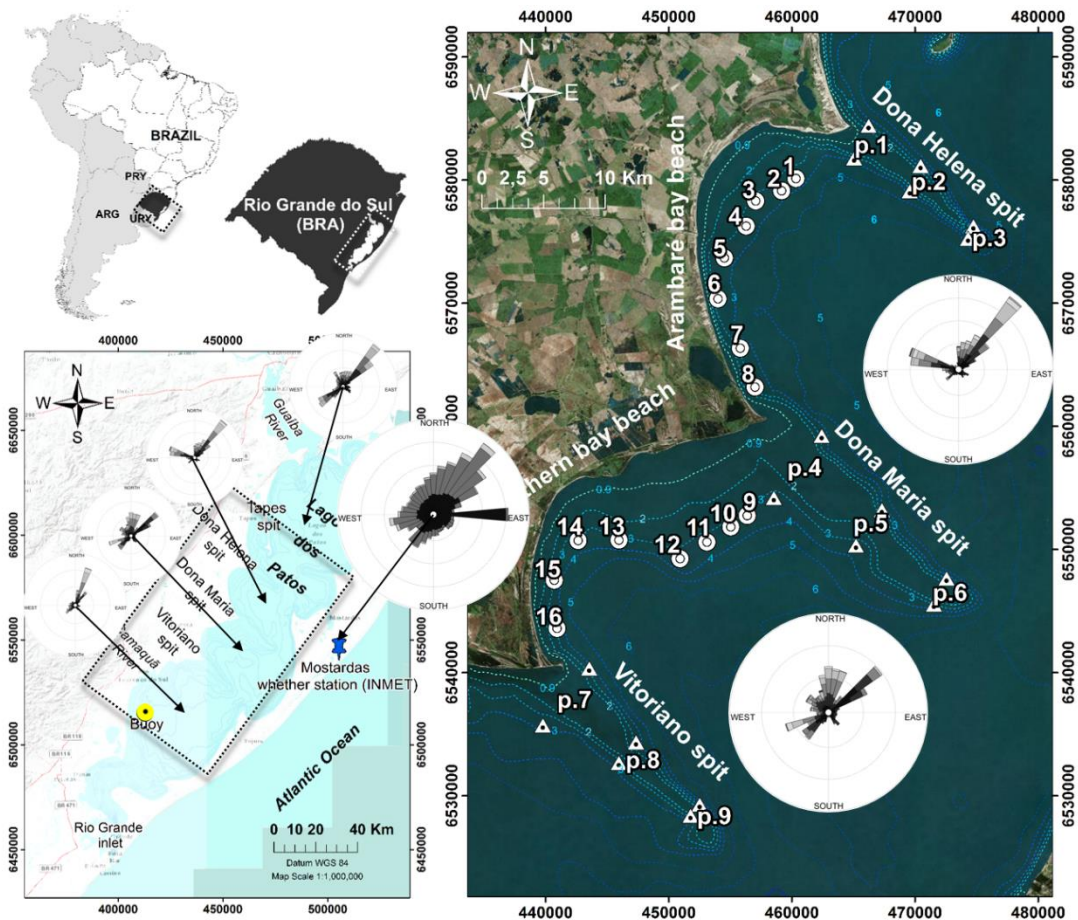


Figure 1. Study area, with the distribution of control points along the submerged spits to the wave attenuation measurements (triangles), and along the lagoon bay beaches to the alongshore distribution of the wave energy (circles). Locations of the wave buoy (Directional Waverider MkIII) moored at ~6m depth, and the wind recording station (Mostardas/ INMET). Directional wave roses of H_s at deeper waters in the center of each lagoon cell for the year of 2015.

Table 2. Parameters of the submerged lagoon sandy spits (‘cusped spits’) based on the Bathymetric Brazilian Chart. (*W.r.t. N= with respect to the north).

| Cusped Spits | Proximal point | | Centre | | Distal point | | Orientation | | |
|--------------------|----------------|------------|------------|------------|--------------|------------|-------------|--------|--------|
| | Width (km) | Width (km) | Width (km) | Width (km) | Width (km) | Width (km) | W.r.t. N | Facing | Facing |
| Isodepth | ~1 m | ~3m | ~1 m | ~3m | ~1 m | ~3m | | NE | SW |
| Dona Helena | 2.28 | 3.38 | 1.10 | 2.62 | 0.21 | 1.32 | 129.5° | 39.5° | 219.5° |
| Dona Maria | 3.85 | 7.45 | 1.54 | 4.17 | 1.55 | 2.78 | 133.0° | 43.0° | 233.0° |
| Vitoriano | 3.61 | 7.05 | 0.45 | 2.60 | 0.27 | 1.43 | 135.4° | 45.5° | 225.4° |

MATERIAL AND METHODS

The flowchart below (Figure 2) presents the methodology steps of this study and is further explained in the following sections.

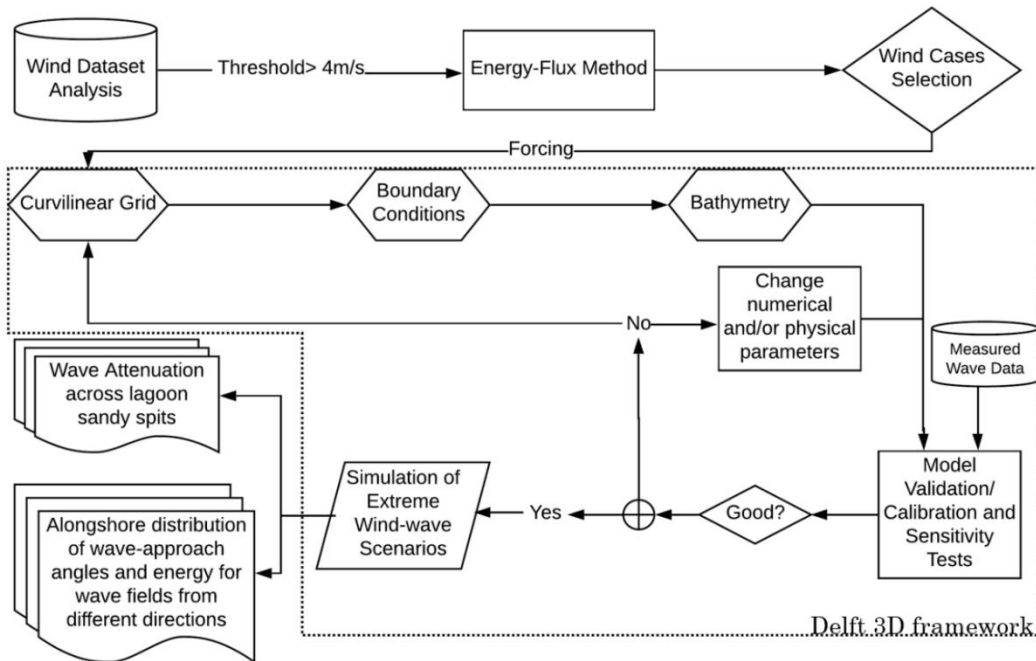


Figure 2. Flowchart illustrating the methodology steps.

The waves in the lagoon are solely generated by wind forcing. Therefore, the wind dataset was first analyzed in order to identify representative wind conditions over the region (Table 1), followed by the selection of wind cases as further detailed.

Wind Case Selection.

Local hourly wind data from 2008 to 2016, collected from Mostardas weather station (INMET Brazil), $31^{\circ}14'53.8''$ S and $50^{\circ}54'22.6''$ W (Figure 1), was first analyzed using the joint distribution function (see Table 1). Then, simulation tests using wind speeds below 4 m/s for the 16 directions (N-NNO, $\Delta\theta = 22.5^{\circ}$) showed that below this threshold, the winds do not generate waves capable of inducing sediment transport. Therefore, wind speeds below 4 m/s from all directions were filtered out, and a method similar to the Energy-Flux-Method (EFM) (Benedet *et al.*, 2016) was applied in the remaining wind dataset (accounting 64.56% of the total time period). The EFM is an input reduction method to determine representative cases (of different magnitudes and directions) from a time series. The classes with the highest magnitude ($> 9\text{m/s}$) were used as forcing conditions (Figure 3).

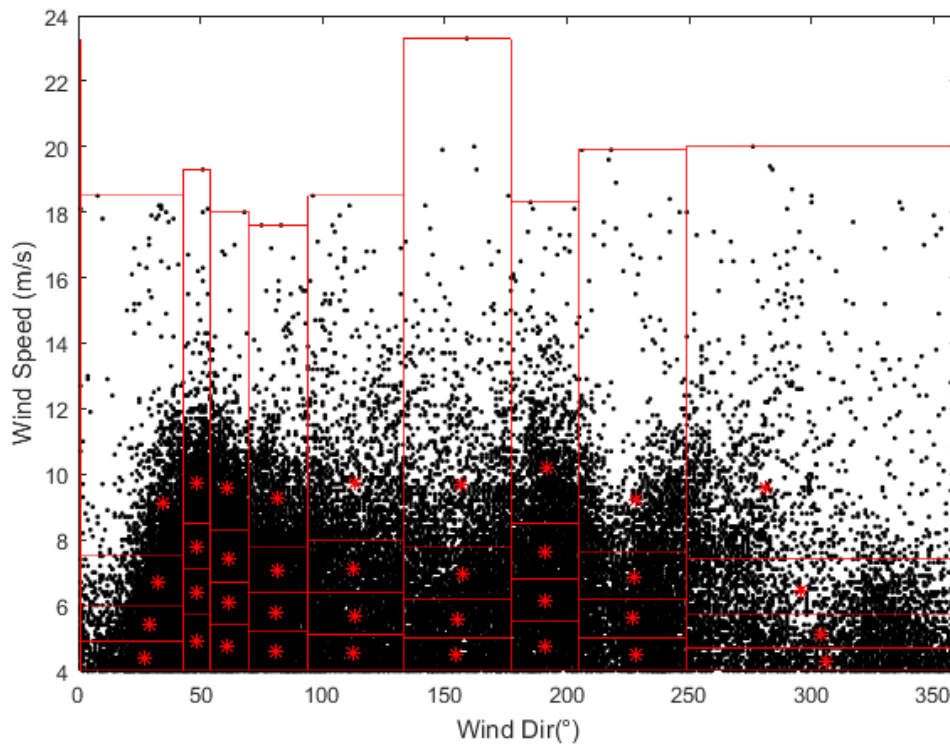


Figure 3. Representation of the discretization of the remaining wind dataset into 36 representative wind cases (red dots).

Wind-wave modelling.

The third generation wave model SWAN (Simulating Waves Nearshore) was used to simulate realistic wind-generated wave conditions within the lagoon water body, through the Wave module, from the Delft3D framework (developed by Deltares in co-operation with the Delft University of Technology), in an online coupled mode with the Flow module (Lesser *et al.*, 2004; Roelvink, 2006), in order to account for the effects of waves on flow and vice-versa. The hydrodynamic conditions (e.g.: velocities, water elevation) calculated in the Delft3D-FLOW module are used as input to the Delft3D-WAVE module (SWAN) and vice-versa through a so-called communication file. SWAN is a fully spectral (in all frequencies and directions) third-generation wave model based on the Eulerian formulation of the discrete spectral balance of action density (Booij *et al.*, 1999; Ris *et al.*, 1999). Further information on the numeric formulations of all relevant physical processes computed in SWAN and used in this research (wave generation by wind - linear and exponential wind growth, (refraction) propagation due to current and depth variations, non-linear triad wave-wave interactions, and wave energy dissipation by whitecapping, bottom friction and depth-induced wave breaking) can be found in Booij *et al.* (1999) and Ris *et al.* (1999).

A curvilinear grid containing 762 and 198 grid cells in the y- and x- directions was used for the Lagoon model. A coarser grid resolution was set outside the interested area, smoothly varying from 200 m up to 600 m, and locally refined in the area of interest (98-200 m) to ensure a good representation of the lagoon margins and the spits' morphology (Figure 4a).

The model domain covers almost the entire water body, disregarding the initial 9 km of the lagoon inlet (less than 4% of the Lagoon length) due to the lack of reliable data to provide boundary conditions. The tidal and sub-tidal signals are filtered out inside the Patos Lagoon and the wind influence on water levels is significantly greater (Moller *et al.*, 1996 and Fernandes *et al.*, 2004). Therefore, for this study, offshore tidal variations were not propagated towards the lagoon. The average discharge of the Guaíba river (988 m³/year) based on Andrade Neto *et al.* (2012) was also used as a boundary condition. At the extreme south (outlet) an open water level boundary with astronomic forcing was used with data provided by Praticagem Rio Grande (Brazil).

The bathymetry data is based on the Brazilian Navy Nautical Chart number 2140 and nine bathymetric profiles from the same source. The Navy Chart presents a scale of 1:270,000 of a survey conducted in 1964. The depth samples were adjusted based on the reduction level measured at Arambaré and São Lourenço Station (0.33 m), and the bathymetric data were interpolated using the grid cell averaging technique in areas with sufficient depth samples, giving special attention to the study area and, where the depth samples were scarce, the triangular interpolation method was applied (Figure 4b). The calibration of the model and the general trends observed are good indications that the bathymetric data, despite not being recent, are a good representation of the study area for scientific research purposes.

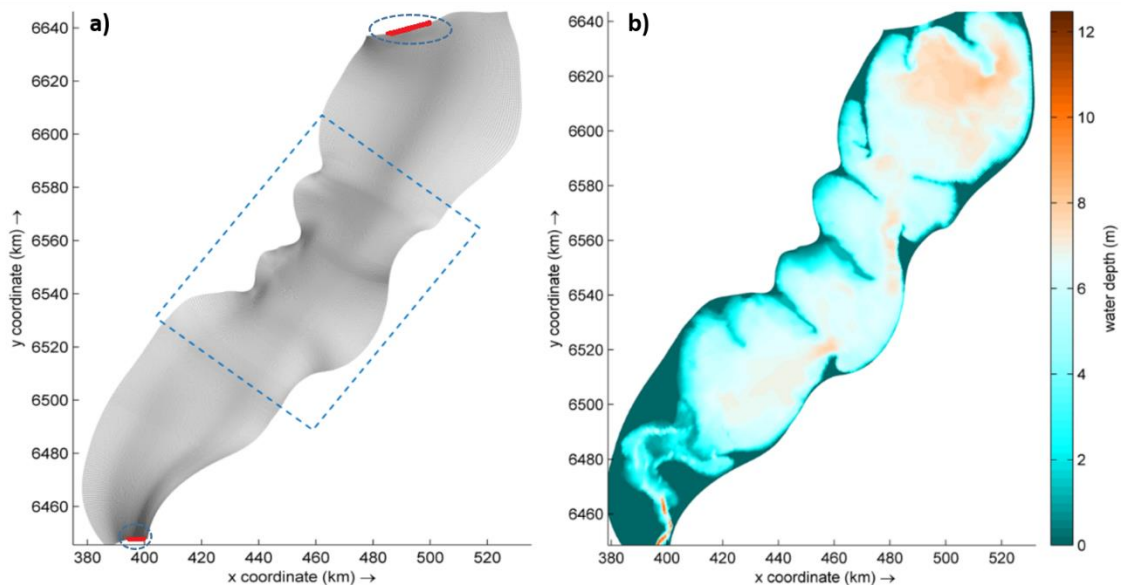


Figure 4. (a) Curvilinear grid with the north and south boundaries highlighted by the dashed circles and, the interest area situated inside the dashed square; (b) bathymetry of the lagoon water body.

Model Calibration/ Validation and Sensitivity Tests.

A series of model tests were simulated with the lagoon model for one month, from 01/30/2015 to 03/03/2015, to test the sensitivity of the physical parameters and to calibrate the model. Also, a longer time-period was considered for the model validation, from February to April, 2015, a time period that co-incident with measured in-situ data when the Waverider Datawell Mark III was deployed (see Figure 1 for location).

The following numerical settings and formulations of the physical processes were tested: (1) The bottom dissipation formulation of Madsen *et al.* (1988) was selected, with the physical roughness of 0.05 m following the value used in Chesapeake Bay by Lin *et al.* (2002) - and the empirical JONSWAP formulation of Hasselman *et al.* (1973), i.e. testing bottom friction coefficients (C_b) with the value $0.038 \text{ m}^2\text{s}^{-3}$ recommended for swell conditions (Hasselmann *et al.*, 1973) and $0.067 \text{ m}^2\text{s}^{-3}$ for wind sea conditions (Bouws and Komen, 1983); (2) the whitecapping mechanism, by (de)activation of the process and by comparing the adapted form of Komen *et al.* (1984), and the revised source term of Westhuijsen *et al.* (2007) and; (3) the wave-wave non-linear triad interactions (ANEXX -A).

The model results were checked against measured data and the quality was measured by the following statistic metrics: Root-mean-square error (RMSE) (1), symmetrical slope (*sym r*) (2), and bias parameter (BIAS) (3). Where P_i is the predicted variable and O_i is the measured variable, N is the number of data, as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2} \quad (1)$$

$$sym\ r = \sqrt{\frac{\sum P_i^2}{\sum O_i^2}} \quad (2)$$

$$BIAS = \frac{1}{N} \sum_{i=1}^N (P_i - O_i) \quad (3)$$

The model outputs of significant wave height (Hs), peak wave period (Tp), U and V components converted from the magnitude and direction were considered for the model validation. The representative model run tests with their results are included in the supplementary material (*Apêndice-D, Apêndice-E, Apêndice-F*).

Model set-up

The physical and numerical settings which conferred a good agreement between the modelled and measured wave parameters (Figure 5), based on the results of the previous runs, are further detailed and summarized in Table 3.

The bottom friction process was represented by the JONSWAP form with the friction coefficient of $0.038 \text{ m}^2\text{s}^{-3}$ (Hasselmann *et al.*, 1973). For the whitecapping process the adapted expression of Westhuysen *et al.* (2007) was used. The depth-induced wave breaking form of Battjes and Janssen (1978) and the non-linear triad interactions of Eldeberky and Battjes (1995) and Eldeberky (1996) were used with default values.

The sensitivity tests showed that an online coupling interval of 1-hour between the WAVE and FLOW modules were most adequate for the study area. The directional space was discretized into 72 directional bins, covering the full space (360°) and the frequency domain ranged from 0.05 Hz to 1 Hz with 24 bins (default).

Table 3. Set of coefficients and parameters in SWAN used for the wind-wave modelling in Lagoa dos Patos, Brazil.

| Physical Process | Formulation | Coefficients/ or Values |
|--|---|------------------------------------|
| Wind growth | Koment <i>et al.</i> (1984) | |
| Depth-induced wave breaking | Battjes and Janssen (1978) | $\alpha = 1; \gamma = 0.73$ |
| Bottom friction | JONSWAP (Hasselmann <i>et al.</i> 1973) | $0.038 \text{ m}^2\text{s}^{-3}$ |
| Non-linear triad wave-wave interactions | Eldeberky and Battjes (1995) and Eldeberky (1996) | $\alpha = 0.1; \beta = 2.2.$ |
| Whitecapping | Westhuysen (2007) | |
| Refraction | Activated | |
| Water density | | 1000kg/m^3 |
| Gravity | | 9.81 m/s |

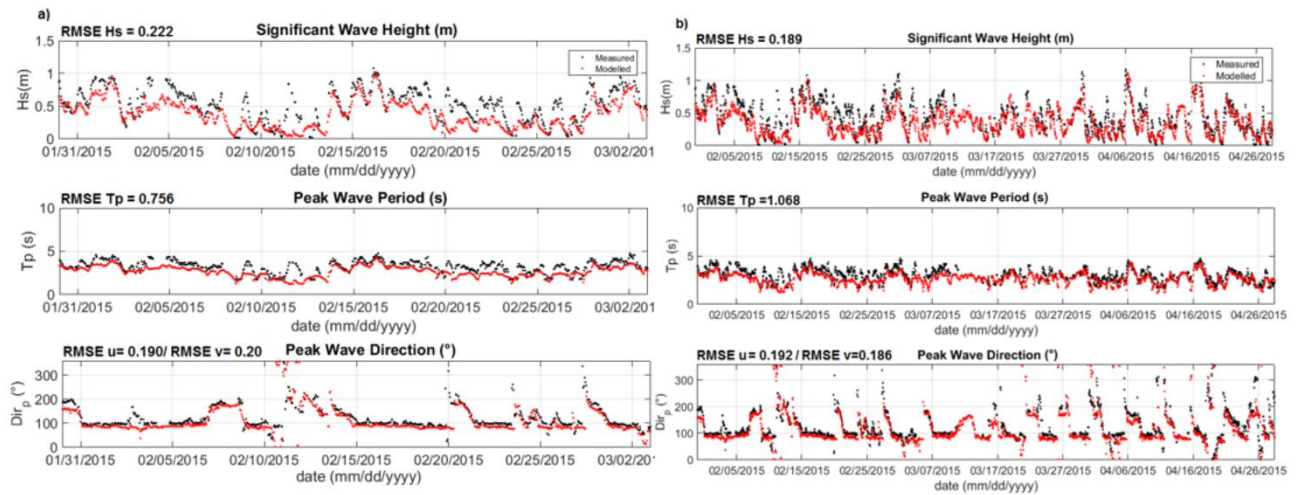


Figure 5. Model validation (Fig. 1 for buoy location). Left column: one month (top) and four months (bottom) of measured vs. modeled significant wave height (Hs) and peak period (Tp) and peak direction (Dir).

Sensitivity Tests and Model Calibration

Considering the numerical settings, the model run using the stationary computational mode (Run 01) showed the worst statistical performance parameters, with a $RMSE_{Tp}$ of 0.98 s of modelled peak wave period (Tp) in comparison to the $RMSE_{Tp}$ of 0.90 s for the run with the same settings (Run 3) in the non-stationary mode. No better results were obtained by using a shorter wave-flow coupling time interval and number of iterations, (120), in the stationary mode (Run 02) (Supplementary Material, *Apêndice-E*), while the computation in the non-stationary mode using shorter coupling time intervals, from 360 min (Run 03), to 180 min (Run 05), provided better model results with respect to the significant wave height and peak wave period (Supplementary Material, *Apêndice-E*).

Among the mechanisms of wave energy dissipation (bottom friction, depth-induced breaking and whitecapping), the highest influence on the modelled significant wave height was the whitecapping (when de-activated – Run 08), with an over-estimation of 60% of the significant wave height and a high root mean square error of 0.42 m, whereas better results were found for the peak wave period ($RMSE_{Tp} = 0.53$ s) (Supplementary Material, *Apêndice-E*).

An improvement on the modelled peak wave period was found by using the Westhuysen *et al.* (2007) approach ($RMSE_{Tp}$ of 0.65s, Run 09), when comparing with the whitecapping formulation of Komen *et al.* (1984) ($RMSE_{Tp} = 0.73$ s, Run 07.2). Also, a minor under prediction of the modelled peak wave period was observed for the Westhuysen *et al.* (2007) formulation (16%, Run 09) than Komen *et al.* (1984), 19% (Run 07.2).

The empirical JONSWAP formulation of Hasselman *et al.* (1973) with the default bottom friction coefficient ($0.067 \text{ m}^2\text{s}^{-3}$) of Bouws and Komen (1983), showed slightly better

model outputs ($RMSE_{H_s} = 0.22$ m, $RMSE_{T_p} = 0.87$ s, $RMSE_V = 0.20$, $RMSE_U = 0.20$ – Run 10) than the approach of Madsen *et al.* (1988), with the default coefficient of 0.05 m ($RMSE_{H_s} = 0.23$ m, $RMSE_{T_p} = 0.91$ s, $RMSE_V = 0.22$, $RMSE_U = 0.20$ – Run 11). Furthermore, the lower JONSWAP bottom friction coefficient of $0.038 \text{ m}^2\text{s}^{-3}$ (Run 06) proposed for swell conditions by Hasselmann *et al.* (1973) provided better model results in Lagoa dos Patos than the high value of $C_b = 0.067 \text{ m}^2\text{s}^{-3}$ (Run 10) suggested for wind-driven seas by Bouws and Komen (1983) (Supplementary Material, *Apêndice-E*).

The modelled wave parameters did not show higher sensitivity with the deactivation of the non-linear triad wave-wave interaction process (Run 12-Run 05, deactivation-activation respectively). Other combinations were also tested and did not show a significant impact on the model results either.

Alongshore Wave Energy and Angles of Incidence.

The spits' morphodynamic evolution is intrinsically related to the incident wave field, more specifically; the angle of wave incidence ($\varphi - \theta$) and the alongshore wave energy gradients. To investigate the action of these physical mechanisms on the considered coastline, incident modelled wave parameters in the vicinity of the depth of closure (3.3m) – calculated by the Hallermeier (1981) formula – were extracted from observation points along the coast. The angle of wave incidence was taken with respect to the wave direction (φ) and the coastline orientation (θ) and the incident wave energy per unit of crest length (in kW/m) was calculated by the following equation:

$$E = \frac{1}{2} H_s^2 T \text{ (kW/m)} \quad (4)$$

In which, E is wave energy per unit of crest length (kW/m), H_s is the significant wave height, and T is the peak wave period.

Wave Attenuation

The wave attenuation (Att) across the submerged spits' sandbars was estimated at 3 m depth (depth of closure) in three longitudinal locations along each spit: 1) In the proximal region (closer to the subaerial spit), 2) At the central portion of the spit (middle) and, 3) At the distal portion (towards the central lagoon water body) (Figure 1).

The measurements were made as a function of the significant wave height arriving (H_{si}) and outgoing (H_{st}) from the northern and southern flanks of the spits, considering the waves

from the first quadrant (NNE, NE, ENE) and vice-versa, considering the waves from the third quadrant (S-SSW and SW) by using the following simple equation:

$$Att = 1 - \left(\frac{H_{st}}{H_{si}} \right) \times 100$$

The wave fields propagating across the short lagoon axis (E, ESE, and SSE) were not included on the measurements of wave attenuation by the spits, due to the spits' orientation and the basin shape.

RESULTS

This section is divided into two main topics; i.) The results of wave attenuation by the spits are first presented, followed by ii.) The alongshore variability of wave energy input along the nearshore region of the lagoon bay beaches [specifically, the incident wave energy (W/m) and associated angle of incidence to the shore ($\varphi-\theta$)], considering different directions of wave generation.

Wave Attenuation over Lagoon Sandy Spits.

A great variability of wave attenuation is observed along different portions of the spits, and it varies for different directions of wave generation, from 18 % up to 46 % (Figure 6).

Maximum significant wave heights occur at the south of the first lagoon cell at a depth of 7 m (up to 0.96 m for the NE waves and 1.05 for the SSW waves). The wave direction closely follows the wind direction, until the waves refract over the submerged sandy spits. Energetic waves propagating across the long lagoon axis are attenuated and refracted by the analyzed cusped spits towards the western lagoon bay beaches, except the SW waves which experience minimal refraction while crossing the submerged spits due to the nearly perpendicular wave-approach angles ($0.7^\circ-7.4^\circ$)(Supplementary material, Annex-D/ *Apêndice-G*).

The NNE, NE and ENE waves are mainly attenuated at the proximal and central regions of the northern (Dona Helena) and central (Dona Maria) spits, in a rate of 39 % to 46 % of wave height attenuation, while less attenuation occurs at their distal portions (Figure 6a, b). The distal portion of Dona Helena spit showed the smallest rates of wave attenuation for all wind-wave scenarios, with a minimum rate of 18 % for the SW waves up to a maximum of 26 % for the NE waves (Figure 6a, see Figure 1 for point location).

For the southern spit (Vitoriano), in turn, there is greater attenuation of the NNE, NE and ENE waves which occurs at its distal portion (Figure 6c). NNE-ENE waves reach this sector

with higher incident energy (amplitude) because these directions of wave generation have a larger fetch length and width, and also propagate through deeper waters (Table 4, Annex-D/ *Apêndice-G*).

The S, SSW and SW waves, in contrast, are mainly attenuated on the proximal (41% - 44%) and central (33% - 34%) portions of Vitoriano spit (southern spit), and are less attenuated on the distal portion (27 % - 29 %) (Figure 6c).

The waves generated by the S-SSW wind case approach the southern flank of the spits with the SSW and S directions. Higher degree of attenuation of S, SSW and SW waves occurs in the central (40% - 41%) and distal (39% - 40%) portion of Dona Maria spit and minor rates (but still representative) of attenuation occurs at the proximal region (35% - 37%).

Dona Helena spit (north), in turn, shows higher attenuation of S, SSW and SW waves in the proximal (38% - 42%) and central (33% - 36%) regions (Figure 6a).

After being transmitted by the spits, the waves do not reach the same size as they had before dissipating over the upwind spit. Even in regions with enough fetch for the reformation (the southern coast of the bay beaches for the NNE, NE and ENE waves, or, the northern coast of the bay beaches for the SW, SSW and S waves), mainly due to the reduced depths on the second and third lagoon cells.

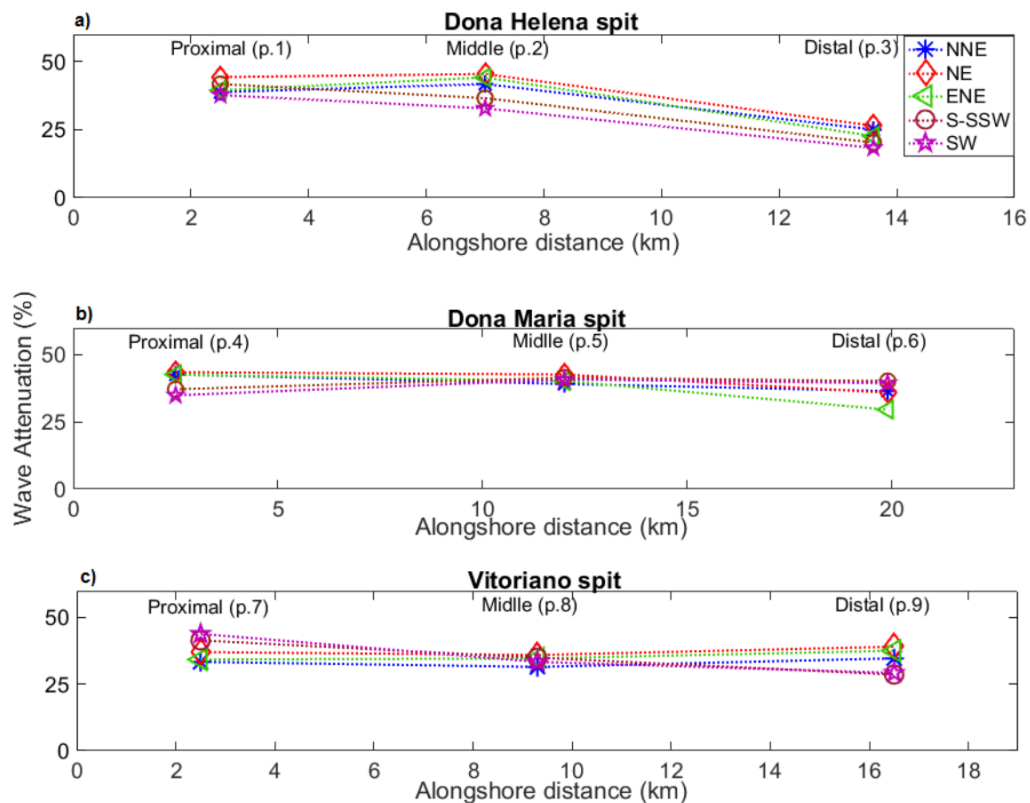


Figure 6. Wave attenuation (%) along different portions of Lagoa dos Patos' sandy spits for waves generated by extreme wind cases blowing across the long lagoon axis, from the NNE, NE, ENE, S-SSW and SW directions. The control points used for the measurements of wave attenuation are demonstrated in figure 1 (p.1 to p.9). Dotted

lines highlight the different degrees of wave attenuation along different portions of the spits for various wave directions.

Table 4. Incident wave energy along different portions of the spits for wave fields from different directions.

| Scenarios | | NNE | NE | ENE | SW | S-SSW |
|-----------------------|-----|--------|-------|-------|-------|--------|
| Cuspate Spits | | (W/m) | (W/m) | (W/m) | (W/m) | (W/m) |
| Dona | p.1 | 704.7 | 1061 | 985 | 545.1 | 1057.8 |
| Helena spit | p.2 | 1085.9 | 1433 | 1353 | 693.5 | 1166.6 |
| | p.3 | 1126.4 | 1385 | 1266 | 811.6 | 1248.9 |
| Dona | p.4 | 953.4 | 1297 | 1183 | 601.3 | 1040.4 |
| Maria spit | p.5 | 925.4 | 1183 | 1005 | 819.2 | 1180.1 |
| | p.6 | 917.2 | 1031 | 804 | 984.8 | 1358.6 |
| Vitoriano spit | p.7 | 664.3 | 867 | 956 | 879.3 | 1373.8 |
| | p.8 | 786.4 | 1034 | 1034 | 945.0 | 1335.0 |
| | p.9 | 939.4 | 1170 | 1104 | 873.5 | 1028.7 |

Alongshore distribution of the wave energy and incident wave angles ($\phi-\theta$) on lagoon bay beaches.

The waves generated by the NNE, NE, and ENE winds show greater similarity on the alongshore distribution of the incident wave characteristics: typically the establishment of shadow zones on the northern coast of the beaches (sub-areas of local wave generation); an increase of incident wave energy towards the south; a very low occurrence of oblique wave incidence, which is restricted to the semi-protected sector of the coast (Figure 7, point 3 of the NNB and point 12-14 of the SBB) and; smaller to virtually shore-normal wave-approach angles at the downdrift section of the beaches (Figure 7a, b, and c, point 8 of the NBB and point 16 of the SBB).

On the northern bay beach, the incident alongshore energy distribution of waves generated by NNE, NE and ENE wind cases, increases towards the south, as follows: a) from 244 W/m to 761 W/m for the NNE case, b) from 368 W/m up to 1008 W/m for the NE case, and c) ENE - from 429 W/m up to a maximum of 1002 W/m, decreasing to 979.0 W/m at the extreme south.

The southern bay beach presents a similar pattern; however, it shows a larger shadow zone (and thus a larger sub-area of local wave generation), less alongshore incident wave energy intensity allied to lower energy gradients between the beach extremities, as follows; a) NNE – 270-499 W/m, from the north to south, b) NE – 349-719 W/m and, c) ENE - 383-718 W/m (Figure 7a, b, and c).

Thus, the northern coast of the lagoon bay beaches (leeward coast of the spits) is sheltered from the NNE, NE and ENE waves, while the southern sectors (the updrift coast of the spits) is exposed to higher incident wave energy with relatively small to virtually shore-normal approach-angles, as follows; $\varphi-\theta_{NNE} = 16^\circ$, $\varphi-\theta_{NE} = 7^\circ$, $\varphi-\theta_{ENE} = 0.5^\circ$ in the southern coast of the northern bay beach, and $\varphi-\theta_{NNE} = 25^\circ$, $\varphi-\theta_{NE} = 14^\circ$, $\varphi-\theta_{ENE} = 5.0^\circ$ in the southern coast of the southern bay (Figure 7a, b, and c).

The E wave scenario also resembles the NNE, NE and ENE wave scenarios. However, an overall high incident wave energy is observed on both bay beaches, with minor energy gradients between the beach extremities. It ranges from 543 W/m to 799 W/m, from the north to the south coast of the northern bay beach (Arambaré), and from 451 W/m to 822 W/m - from the northern to the southern coast of the southern bay beach. The higher alongshore incident wave energy of this scenario is counteracted by smaller incident angles ($\varphi-\theta < 10^\circ$) on the central and south sector of the northern bay beach (Arambaré) and the southern sector of the southern bay beach (Figure 7d).

There is a very low occurrence of oblique wave incidence on both bay beaches (less than 19%) for wave fields from different directions (NNE, NE, ENE, E, S-SSW, and SW). On the Arambaré coastline (in the semi-protected sector of the northern bay beach, between observation points 2-3), the waves generated by the NNE, NE, ENE and E winds approach at oblique angles but with reduced energy because of the dissipation over Dona Helena spit. As opposed to the S-SSW wave field, whose oblique wave incidence is associated with an accentuated energy, due to the larger fetch length for the wave reformation after crossing Vitoriano spit. Though, this beach section is characterized by a shoreface with a wider and flatter slope.

On the southern bay beach, the oblique wave incidence occurs along the transitional morphological zone (with an accentuated narrowing) of the shoreface width (point 12 and point 14), mainly at point 14. Point 12 marks the beginning of the morphological transition zone of the shoreface, where it presents wider width with a smoother slope, while point 14 marks the end of the morphological transition zone, which is characterized by a reduced intensity of the incident wave energy due to the enhanced wave refraction in this morphological transitional zone of the shoreface (ANNEX – C).

The clockwise rotation in the direction of wave generation, from the NNE to the E, increases the exposure of both analyzed beaches, and the susceptibility of the northern sector of the coast to the oblique wave-approach (Figure 7a, b, c, and d). Likewise, the counter-

clockwise rotation, from the SW to the SSE directions, increases the coastline exposure (Figure 7, f, g, and h). Both bay beaches present an accentuated degree of exposure to waves generated by the ESE winds, propagating through the transversal axis of the lagoon, and thus presenting high incident wave energy with quasi-homogeneous alongshore distribution (Figure 7e), due to the minor influence of the spits on this wave field.

Higher incident wave energy intensity (decreasing towards the south), is also observed for the SSE wave case on both bay beaches, allied to an increased occurrence of oblique wave-approach angles (Figure 7f).

In regards to the S-SSW scenario, a decrease in the alongshore incident wave energy is also observed from the north to the south coast of Arambaré (889.8 W/m-286 W/m) and from the north to the south of the southern bay beach (from 1104 W/m to 254 W/m, respectively). The extreme south of the Arambaré coast (ENE facing orientation) is wave-sheltered, while transversal wave propagation is observed on the downcoast sector of the southern bay beach (E facing orientation) (Figure 7g).

In the case of the SW waves, a very large wave shadow zone is observed along the central and south sectors of the northern bay beach and, along the south sector of the southern bay beach (Figure 7h), while the northern coasts of Arambaré (S facing orientation with an accentuated curve to the SE) and the northern coast of the southern bay beach (generally SSE facing orientation) are exposed (Figure 7h).

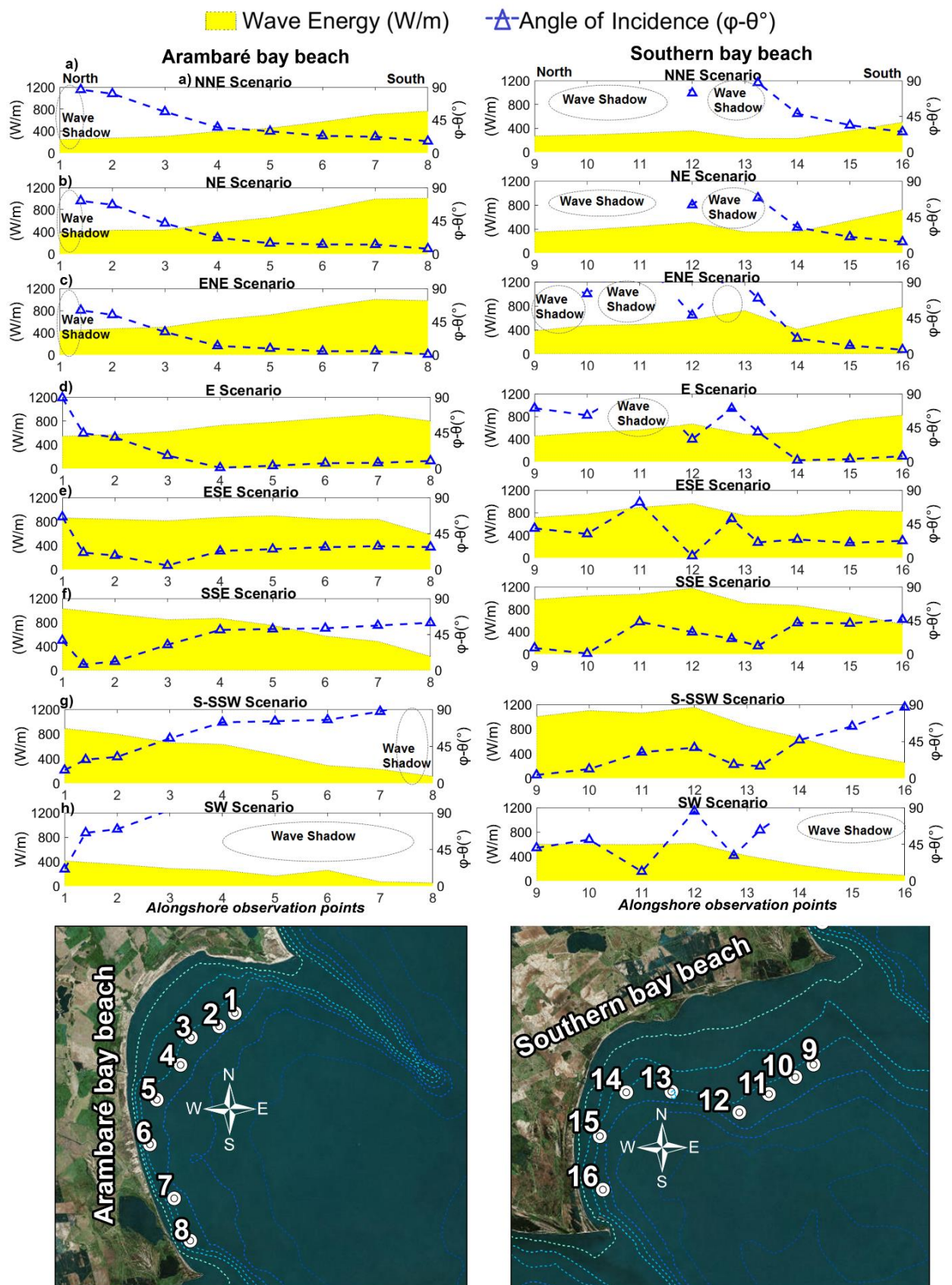


Figure 7. Alongshore distribution of the incident wave energy (W/m) per angle of wave-approach ($\phi-\theta$ triangles with dashed lines), including the wave shadow zones for the northern, Arambaré (from pto.1 to pto. 8) and southern bay beaches (from pto.9 to pto. 16) resultant of extreme wave field scenarios from various directions; from (a) NNE, (b) NE, (c) ENE, (d) E, (e) ESE, (f) SSE, (g) S-SSW, to (h) SW.

DISCUSSION.

The wave attenuation by the lagoon sandy spits is discussed in the first section, in which the possible interactions of the wave dissipation mechanisms are assessed through the results of the sensitivity tests and comparisons with other wave attenuation studies. The second section concerns to the alongshore distribution of the wave energy and associated angles of incidence along the lagoon coastlines for representative wave field scenarios.

Wave Attenuation.

The depth-induced- and partial depth-induced wave breaking over the sandy spits seems to be the main wave dissipation mechanism in the lagoon (see Supplementary Material, Run 08). This finding is consistent with other studies in depth-limited wave growth situations (Westhuysen, 2010; Xu *et al.*, 2013), where the majority of the breaking events were associated with excessive wave steepness. For instance, Westhuysen (2010) has shown that SWAN normally underestimates the wave heights and periods on shallow flats due to the underestimation of dimensionless ratio H_{m0}/d (significant wave height/local water depth) of the locally generated wind sea, thus proposing a new expression to resolve this model inaccuracy in finite depth environments.

The wave attenuation shows great variability along the spits (Figure 6), which can be associated to i) their variable morphology (a wider submerged shallow surface near to the root of the spits with an accentuated narrowing until its distal portions, ending up in deeper waters, see Figure 1; Table 1), and to ii) the incident wave characteristics (amplitude), which depends on the direction of wave generation and the respective fetch length and width, and the water depth (Supplementary material, Annex-D).

The higher degree of attenuation of larger amplitude waves occurs at the distal portion of Vitoriano spit (NNE, NE and ENE waves) and at the distal portion of Dona Maria spit (S-SSW and SW waves) (Figure 6), due to the larger fetch lengths and widths to those directions of wave generation, and because they propagate in deeper waters (Supplementary material, Annex-D). Similarly, Hardy *et al.* (1990) observed the influence of the wind regime and the fetch length and depth to variations in the wave height on the lagoon-reef system of the Great Barrier Reef, Australia, without follow up investigation.

Those results corroborates and complements Toldo *et al.* (2006a) study who observed that for a certain location of the lagoon coastline and wind condition, the incident wave characteristics (H_s and T_p) are defined by the fetch and depth, thus demonstrating the limiting effect of the lagoon basin shape in the wave growth. Those authors also emphasized the

establishment of sub-areas of local wave generation (by the surrounding landforms – the spits) which assumes greater importance in the final stages of cusped shorelines development. As the larger the wave shadow zone (and larger dimension of the cusped feature), the larger the influence of the sub-area of local wave generation (ex.: leeward side of Dona Maria spit).

In embayed beaches on the ocean shore, Vieira da Silva *et al.* (2018) showed the dependence of the coastline orientation (in association with the local bathymetry) on alongshore variations in the wave attenuation process, with respect to the incoming wave direction. Those authors also highlight the importance of wave refraction on the alongshore variability of wave attenuation on non-straight coastlines. In the Lagoa dos Patos cusped coast case, a similar alongshore variation in the wave attenuation is observed depending on the direction of wave generation, and the coastline exposure (Figure 7). Although refraction effects are very limited in the nearshore region of the lagoon bay beaches (due to the narrow shoreface and the short-crested generated waves), the wave refraction over the submerged spits has a significant influence on the degree of exposure of the adjacent coastline.

Moreover, the enhanced wave refraction on the morphological transition zone of the shoreface promotes a slight reduction of the incident energy on the downdrift coast of the bay beaches (the updrift coast of the spits), a process more evidenced on the southern bay beach.

The NE, ENE and E waves generated by the predominant winds (Table 1) are mainly attenuated while crossing the proximal and central region of the northern (Dona Helena) and central (Dona Maria) spits, with a rate of 39% to 46% respectively (Figure 6). The reduction of transmitted energy to the adjacent coastline at the leeward side of the spits (Figure 7) demonstrates the control of the wave attenuation in the stability of the adjacent coast. This is in agreement with the study performed by Miranda *et al.* (2019), which observed a prevailing stability trend on the medium-term analysis of the shoreline change (1984-2013), with a slight progradation trend along the northern coast of the bay beaches (leeward side of the spits).

This stable behavior of the coastline (Miranda *et al.*, 2019) can be associated with the cusped spits' influence on waves through the wave attenuation process and the wave sheltering provided by the spit.

Therefore, the lagoon sandy spits, similarly to a submerged breakwater (Jackson *et al.*, 2010) and a barrier reef (Hegge *et al.*, 1996; Lowe *et al.*, 2005), act as natural protection of the coast by reducing the transmitted energy to the adjacent bay beaches on the leeward side of the spits, especially during episodic storm wind events acting over the longer lagoon axis (NNE, NE, ENE, S-SSW and SW). Moreover, even the waves that pass over a submerged breakwater

without breaking are reduced in energy (Jackson *et al.*, 2010) as are the waves that pass over the submerged cusped spits during lagoon wave fields of moderate energy (not shown here).

Thus, allied to the wave sheltering effect promoted by the presence of the emerged cusped features (Ells and Murray, 2013), the wave transformation processes (especially attenuation and refraction) over the submerged spits are also an important control on the stability of the adjacent coastlines.

Nonetheless, the wave attenuation over the shallow submerged crest of the spits is also responsible for its progressive erosion. Wave-induced sedimentary reworking first evidenced by Toldo (1991) through sediment and bathymetric profile analysis and confirmed by Miranda *et al.* (2019) which observed the cannibalization process of the spits due to the reduced sediment supply, as the erosion of the adjacent beaches are their main sources of sediments.

Moreover, this continued natural wave-induced erosion of the submerged spits can lead to a decrease in the effectiveness of the wave attenuation into the lagoon, which in a future scenario (from decades to centuries) can lead to an increase in the movement of the lagoon shorelines.

Alongshore Distribution of Wave-Approach Angles (φ - θ) and Energy (W/m) on a Cusped Shoreline.

The alongshore distribution of wave energy and incident directions of predominant waves are important controls on the spatial variability of morphological changes in wave-dominated coasts, especially on the morphology of spits which are highly controlled by the incident wave characteristics and the sediment supply (Zenkovitch, 1959; Rosen, 1975; Ashton *et al.*, 2001; Allard *et al.*, 2008; Petersen, 2008; Lopez-Ruiz *et al.*, 2012; Murray and Ashton, 2013; Escudeiro *et al.*, 2019).

For fetch-limited water bodies, the high proportion of oblique wave-approach angles generated by winds blowing across the long fetch is the primary forcing control on the evolution of shoreline features in a cusped form (Zenkovitch, 1959; Rosen, 1975; Ashton *et al.*, 2009). On Lagoa dos Patos, a very low occurrence (less than 19%) of oblique wave incidence, between 30° to 60°, is observed along the coast for different wave field directions, especially for those propagating across the long lagoon axis (Figure 7). This is attributed to the influence of the cusped spits themselves on the lagoon wave climate.

The influence of the cusped spits on the lagoon wave climate in their final stages of development (~half of the lagoon width) was first highlighted by Zenkovitch (1959), who reported that the spits act as obstacles to the free wave propagation across the long lagoon axis,

by impeding them to maintain their former size, and thus reducing their influence on the coast and dissipating the tendency towards asymmetry. After that, the analytical Coastline Evolution Model (CEM) developed by Ashton *et al.* (2009) to represent the large-scale evolution of cusped features in an elongated lagoon water body showed that the growth of cusped features changes the local wave fields, leading to a reduced local proportion of high-angle waves despite the regional instability. This behavior was observed in the modeled features of CEM, and in the natural cusped features of the North Carolina Coast (EUA) (Ashton and Murray, 2006b) and now in Lagoa dos Patos, as it can be seen by the incident wave angles in the nearshore region of the lagoon bay beaches (Figure 7) and the directional wave roses in the center of each lagoon cell (Figure 1) with the resultant waves oriented at oblique angles to the shore.

The results achieved here are in accordance with Ashton *et al.*'s (2009) observations, notwithstanding that for this study it seemed more reasonable to use the wave parameters at the depth of closure instead of at “deeper waters” (before refraction and shoaling), as refraction is virtually absent on the analyzed bay beaches and the submerged spits exert an important influence on the wave propagation patterns due to their shallow crest depth (~1m) and wider width (Table 1, Supplementary Material, Annex-D).

The direction of wave generation and the wave transformation processes over the submerged spits (mainly refraction and the dissipation mechanisms) in association with the lagoon coastline configuration (orientation) demonstrate important controls on the alongshore distribution of the wave energy (W/m) and incident angles ($\varphi-\theta$). Such that similar patterns of local wave angles and energy occur along the lagoon bay beaches coastline for wave fields from different directions (Figure 7).

An increase in the wave sheltered coastal area is observed for the wave fields propagating across the long lagoon axis, which are coincident with the bimodal wind regime – dominant NE winds throughout the year and prevailing SW and southerly winds during autumn and winter (Delaney, 1965; Stech and Lorenzetti, 1992; Tomazelli, 1993; Klein, 2012). The degree of sheltered coast is related to the larger projection (dimension) and orientation of the emerged spit. The larger the subaerial spit, the greater is the extension of the wave sheltered coastal area for wave fields propagating across the long lagoon axis. This can be seen by the larger projection of the emerged Dona Maria spit and the larger extension of sheltered coast of the southern bay beach to the NNE, NE and ENE waves. Likewise, there is significant sheltering of the Arambaré coast (northern bay beach) from the SW waves (Figure 7).

The wave refraction over the spit's sandbars also demonstrates an influence on the degree of shadowing. Reduced refraction is observed when a better alignment of the cusped feature to the incident wave direction occurs, which also results in a larger wave shadow zone (e.g.: southern coast of Arambaré to the SW waves, and northern coast of the southern bay to the NNE, NE and ENE scenarios) (Supplementary material, Annex -D).

Despite the similar pattern in the alongshore distribution of the incident wave characteristics at a regional level (Figure 7), the degree of exposure differs between the two analyzed bay beaches to waves under the same wind condition. Similar behavior was observed on estuarine beaches in New Jersey (USA) by Jackson and Nordstrom (1992, 92) who stated that “processes that are similar at regional level express themselves differently at local level because of site specific controls”. For the authors' case, the shoreline orientation affects the degree to which refracted ocean waves alter the incident wave field. In this case, the projection (dimension/amplitude) of the emerged cusped spits and its submerged morphology controls the extension of shadowed area and how the waves are modified (attenuated and refracted) by the spits exerts an important control on variations in the incident wave characteristics along the lagoon shores.

The low occurrence of oblique wave incidence (less than 19%) from waves generated by winds blowing across the long lagoon axis is attributed to the advanced stage of development of the analyzed cusped features, in which the coastline tends to be reoriented in accordance to the predominant wave directions in a cusped-like shape.

The shoreline reorientation process is known to be driven by strong gradients in the alongshore sediment transport due to the high proportion of oblique wave angles to the shore (Zenkovitch, 1959; Rosen, 1975; Ashton *et al.*, 2001; Ashton and Murray, 2006a, 2006b). In this case, not only is there a limited occurrence of oblique wave angles of incidence, but the restricted oblique incidence of the predominant waves has reduced energy due to the dissipation by the spits.

The waves propagating across the main lagoon axis are assumed to be the main drivers of morphological changes into elongated lagoons (Zenkovitch, 1959; Rosen, 1975; Toldo *et al.*, 2003; Ashton *et al.*, 2009). In the Lagoa dos Patos case, it is observed that a strong relationship of mutual co-adjustment exists between the morphology and the hydrodynamics (specifically the incident wave characteristics) in a manner to confer a reduced proportion of oblique wave incidence and high effectiveness of the wave attenuation process along the lagoon margins, especially for the wave fields generated by the winds blowing across the long lagoon axis.

Whereas, the wave fields generated across the short lagoon axis assume greater importance in the morphological response on this stage of the lagoon development. This is attributed to the minor influence of the lagoon cusped spits in these wave fields (by the wave-sheltering and attenuation). Result which agrees with the first observations of Zenkovitch (1959), who stated the increased role of waves generated across the short lagoon axis on the final stages of the water body development. A consequence of the increased curvature radius of updrift beaches with the lateral growing of the paired cusped spits, causing increased fetch lengths with the augment in the lagoon cells width.

CONCLUSION

This work investigates the wave attenuation and alongshore variability of wave energy input [specifically the energy (W/m) and angle of incidence to the shore ($\varphi-\theta$)] along the nearshore region of a lagoon cusped shoreline in the west coast of Lagoa dos Patos by using a process-based model (Delft3D) validated with measured wave data.

The large-scale sandy spits on the landward margin of Lagoa dos Patos are shown to be responsible for the attenuation of waves generated during representative energetic wind conditions over the lagoon water body (by up to 46%). Furthermore, wave dissipation varies along different portions of the spits (i. Proximal, closer to the root; ii. Central, and iii. At the distal end), from 18% to 46%, depending on each spit's morphology and the incident wave properties (which are closely related to the direction of wave generation and the respective fetch length and width, and the water depth). Therefore, the fetch (the lagoon coastline configuration) and the bathymetry (the submerged morphology) controls the wave attenuation along the lagoon coastlines.

Elucidations of the influence of cusped spits of Lagoa dos Patos with respect to the degree of exposure of the lagoon beaches were also demonstrated. The cusped features influence the lagoon wave climate and consequently the energy input entering the nearshore region of the bay beaches by the wave sheltering effect, acting as obstacles to the free wave propagation, and by the wave transformation processes over the submerged spits, mainly through the dissipation mechanisms (attenuation) and refraction.

Therefore, the wave attenuation over the spits is an important control on the stability of the adjacent coastline due its buffering effect during high wave energy events within the lagoon. This process is also responsible for its progressive erosion, and in a future scenario (from decades to centuries), it is expected to have implications for the stability of these lagoon bay beaches in terms of increasing shoreline changes.

The results presented here characterized the wave forcing condition entering the nearshore region of the rhythmic coastline of a mature elongated lagoon (Lagoa dos Patos, Brazil), in which alongshore wave energy gradients are observed along the cusped coast. However, there is a limited occurrence of oblique wave incidence (less than 19%), for wave fields from different directions (NNE, NE, ENE, E, S-SSW, and SW), especially for the predominant NE and ENE waves, for which oblique wave incidence is restricted to the semi-protected sector of the beach (beach section with a wider and gentle sloping shoreface), and for dominant SW waves (associated with the passage of cold fronts) which presents a larger wave shadow zone.

Ultimately, this type of study can also be translated to other study areas (eg.: estuarine beaches and embayed beaches on the ocean shore) and can also inform studies of coastal protection measured with low crested and submerged structures, such as detached breakwaters and artificial reefs.

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CAPÍTULO 5. SEDIMENT BUDGET OF A CUSPATE SHORELINE AND ITS INFLUENCE ON SPIT DEVELOPMENT – LAGOA DOS PATOS, BRAZIL



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Sediment Budget of a Cuspate Shoreline and its Influence on Spit Development– Lagoa dos Patos, Brazil.

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ABSTRACT

This paper quantifies the sediment budget of a cusped shoreline in a coastal lagoon (Lagoa dos Patos, Brazil) and its influence on cusped spit development, also identifying the main longshore sediment transport patterns and investigating the spit's morphological controlling factors. To do so, representative wind conditions (direction and speed) were used to force the validated lagoon wave model utilizing the process-based modelling suite Delft 3D. Representative wave cases were defined, the potential sediment transport was computed along cross-sections and the annual sediment budget was estimated. A pattern of inter-related source and storage areas occurs along the bay beaches. Short-term nodal zones in the longshore drift were identified (convergent and divergent), which have an influence on the regional sediment budget. Littoral cells with the occurrence of convergent nodal zones show positive sediment budget and littoral cells with divergent nodal zones show negative budget. The littoral cells in the center of the bay beaches were identified as temporary storage areas, which is mainly related to the decrease in the longshore flux due to the narrowing in the shoreface width and to the decrease in the angle of wave approach of the predominant NE-E waves due to changes in the shoreline alignment. In contrast, the southern coastal segments of the bay beaches are the main sources of sediments to the submerged portion of spits, even under moderate wave energy conditions. Moreover, local conditioning factors such as coastline exposure and the shoreface morphology affect the longshore transport within the bays, which controls the amounts of sediments supplied to the spits, and thus their further development, in a feedback process.

Keywords: Littoral/longshore drift, coastal lagoon, Delft 3D, cusped spits.

INTRODUCTION

Natural physical processes and human induced changes are drivers of coastal evolution and the sediment transport process is the key element that connects the physical processes with the evolution of coastal morphology. A better understanding of changes in coastal morphology is fundamental as coastal environments are of global importance in terms of their natural resources, ecological value, and as regions of concentrated human activities (Uriarte et al., 2004).

The coastal sediment budget constitutes one of the best approaches to predict coastal changes with sand spits being among the most dynamic coastal landforms of the Earth's surface, comprising multiple physical processes and complex interactions, thus a separate analysis of each of the processes is indicated (Dan et al., 2011; Randazzo et al., 2015), which may vary according to the considered time and spatial scale. Therefore, spits provide an excellent opportunity to investigate the relationship between the “process” and the “form” in a coastal system, in which the sediment transport is the coupling mechanism.

The cusped spits of Lagoa dos Patos, in particular, provide an important geological record of sedimentary processes in time and space (Toldo, 1991). The spits provide natural protection to the lagoon coastlines (Miranda et al., 2020) and also control the sediment budget of the coast.

The term ‘cusped spit’ refers to a prograding shoreline feature developed inside a fetch-limited environment in a cusped-like form. The fetch-limited control results in the prevailing occurrence of oblique wave incidence to the shore across the long axis of the water body (Zenkovitch, 1959; Rosen, 1975; Ashton et al., 2009). The dominant oblique wave incidence to the shore causes strong gradients in the longshore drift, resulting in the reorientation process of the shoreline in accordance to the dominant wave approach directions (Zenkovitch, 1959).

Delaney (1965), Villwock (1984) and Toldo (1991; 2003; 2006a) first attested that the Lagoa dos Patos evolution is in agreement with the model framework of origin and processes proposed by Zenkovitch (1959) due to its geomorphological characteristics, while also highlighting the coincidence between the long lagoon axis and the two main wind components of the regional climate. The long NE-SW fetch results in the intensification of the wave-induced processes and the well-developed cusped spits. A posteriori, Miranda et al. (2020) found the low occurrence of oblique wave incidence to the shore (less than 19%), especially for the predominant waves (NE and ENE), as a result of the advanced stage of development of the analyzed cusped coast.

Ashton et al. (2001), Ashton and Murray (2006a; 2006b) and Ashton et al. (2009) used a 1-line model approach to simulate the evolution of these coastal landforms, through which the authors put the qualitative model of Zenkovieth (1959) into a quantitative framework. These authors noted the role of the “High-Angle Wave Instability Mechanism” (which couples the longshore drift with an evolving morphology under the action of anti-difuse waves) in the development of large-scale rhythmic features, showing that those features are emergent of the shoreline self-organization process, also highlighting the high control that the distribution of the incident wave angles exert on the shoreline evolution. Complementarily, Ashton et al. (2009) found that assymetrical wave climates (with net alongshore sediment transport) lead to more elliptical cells, as is the case of Lagoa dos Patos.

The works of Ashton et al. (2001), Ashton and Murray (2006a; 2006b) and Ashton et al. (2009) treat a set of longitudinal processes that operate at scales larger than the surf zone and even the shoreface. This paper, in turn, aims to contribute to the knowledge of the nearshore sediment dynamics of those types of coasts; elucidating the main longshore sediment transport patterns and investigating the controlling factors while also quantifying the sediment budget of the cusped shoreline and analyzing its influence on cusped spits development.

Geological and Physical Setting

Patos lagoon (Lagoa dos Patos) is located in the southernmost coast of Brazil, in the coastal plain of Rio Grande do Sul state (CPRS). The CPRS is a typical wave-dominated coast, showing a combination of moderate to high wave energy, and a microtidal regime; this allied to a great abundance of sediments and a gentle continental shelf slope has established perfect conditions for the existence of coastal barriers (Dillemburg et al., 2009) and the lagoon system. The coastal plain is composed of four barrier-lagoon systems formed during the Late Quaternary (last 400 ka) associated with four sea level highstands (Tomazelli et al., 2004).

The geomorphological features in the CPRS present a high degree of preservation, being important records of the drivers responsible for its morphogenesis – the majority of them still active nowadays (Toldo, 1991). Also emphasizing that, a mechanistic understanding of the drivers of spit shoreline shape is vital to predict their future evolution and to understand how these coastal landforms may record paleo-environmental information (Ashton et al., 2016).

Lagoon Shore

The lagoon system of Lagoa dos Patos is the largest in South America (> 10,000 m² of area) and is bounded by the most densely populated regions of the state (Porto Alegre, Pelotas and Rio Grande) (Figure 1), with over 3 million residents (Toldo et al., 2003).

The entire system can be classified as a partially closed lagoon (Calliari et al., 2008) with only one restricted and permanent connection with the Atlantic Ocean, a long (20 km length) and narrow (1-2 km width) inlet at the southernmost end of the lagoon (Moller et al., 1996). The inlet morphometry controls the water exchange between the lagoon and the continental shelf sea, which not only filters the astronomical tides but also attenuates the long period oscillations generated offshore (Moller et al., 1996, 2001; Fernandes et al., 2004).

There are two categories of sedimentary environments in the lagoon; the first environment corresponds to the lagoon's sandy margins, and the second larger environment is the muddy, nearly flat interior of the lagoon (Toldo et al., 2000). The lagoon shoreface is an energetic environment, with a mean annual wave-power incident on the lagoon coastlines ranging between 2,057 kW/m on the west margin, and 1,046 kW/m on the east margin (Toldo et al., 2003). The longshore current coincides with the dominant NE and ENE wind directions on the west margin resulting in a dominant littoral drift to the south, while on the east margin the dominant winds are from the WNW and WSW directions causing net drift to the north (Toldo et al., 2003).

On the adjacent ocean coast, the estimated annual longshore sediment transport ranges from 0.60 to 2.63 M m³ y⁻¹ to the north (Motta et al., 2015).

The study area encompasses the west margin (landward) of the central region of the lagoon water body, covering two broad lagoon bay beaches and associated rhythmic sandy spits. The lagoon bay beaches present a noticeable variation of volume and width in the shoreface morphology, and the spits extend underwater (1 meter depth in average), narrowing towards the central lagoon axis (Figure 1).

An assessment of the shoreline changes performed by Miranda et al. (2019) showed the existence of cyclic shoreline behavior with alternate phases of shoreline progradation, stability and recession (less frequent) occurring with interannual periods; in which the edges of the emerged spits were revealed to be highly dynamic sectors. A field survey also identified the presence of geoindicators of intense erosive and depositional signals near the end of the emerged spits (Figure 2 a,b,d,c,e,f,g,h). Notably, the presence of a representative overwash deposit at the updrift coast of Dona Maria spit (Figure 2e) was indentified, a result of storm surges in the lagoon.

The medium-term analysis of shoreline movement (1984-2013), in turn, revealed a prevailing stability trend along both lagoon bay beaches (the main sources of sediments to the subaqueous bars), accounting for 60.4% of the northern bay beach and 73.9% of the southern

bay beach, indicating a reduction in the sediment supply to the spits over the analyzed three decades (Miranda et al., 2019).

Further evidence of the reduced sediment input to the spits is the cannibalization process observed in the subaqueous bar of Vitoriano (Miranda et al., 2019), and the wave-induced sedimentary reworking over the submerged portion of the feature, mainly driven by the prevailing NE waves, in which fine grain sands are removed from the crest of the deposition bars and transported to the southern flank (Toldo, 1991). The absence of colonization of vegetation in the subaqueous bars is further evidence of the accentuated hydrodynamics.

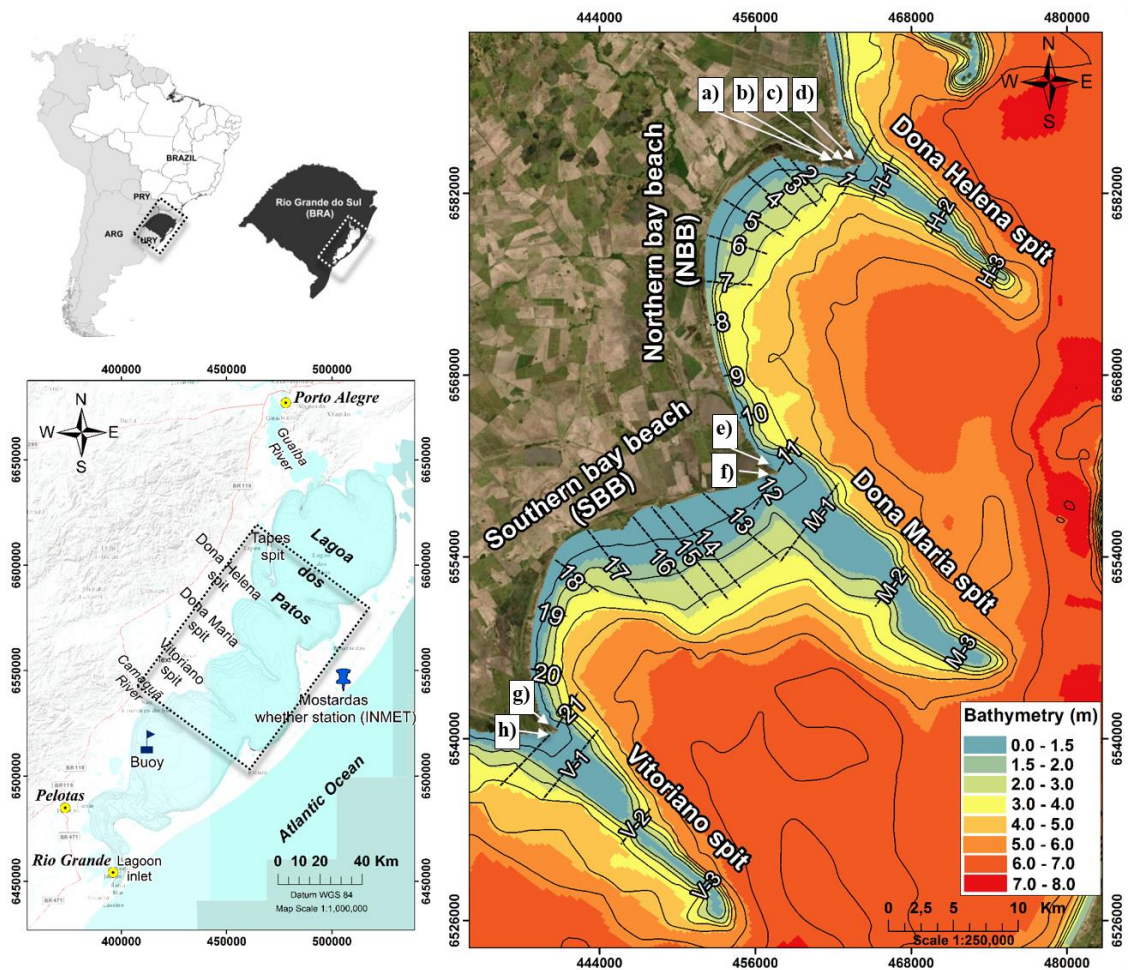


Figure 1. Map of the study area showing the location of the transects where the transport rates were calculated (left panel). The right panel shows the overview of the whole lagoon system and the locations of the wave buoy and the meteorological station. The letters a)- g) correspond to the locations of the photographs presented in Figure 2. Image Source: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, the National Centre for Space Studies (CNES)/Airbus DS, U.S. Department of Agriculture, U.S. Geological Survey, AeroGRID, IGN Spain, and the GIS User Community.



Figure 2. Photographs demonstrating the presence of geoindicators evidencing the occurrence of intense erosive and depositional processes in situ; a) and b) shows peat deposit outcrops and the presence of tree trunks in their life position, c) and d) shows vegetated natural dunes with erosive signals along the southern flank of Dona Helena spit; e) shows washover deposits on the northern flank of Dona Maria spit and, f) shows incipient beach ridges in the southern flank of the spit; g) shows incipient beach ridges on the northern flank of Vitoriano spit and f) shows erosive signals on the southern flank of Vitoriano spit. The photograph's locations are presented in Figure 1.

MATERIAL AND METHODS

The methodology steps are summarized in the flowchart (Figure 3) and further explained in this section.

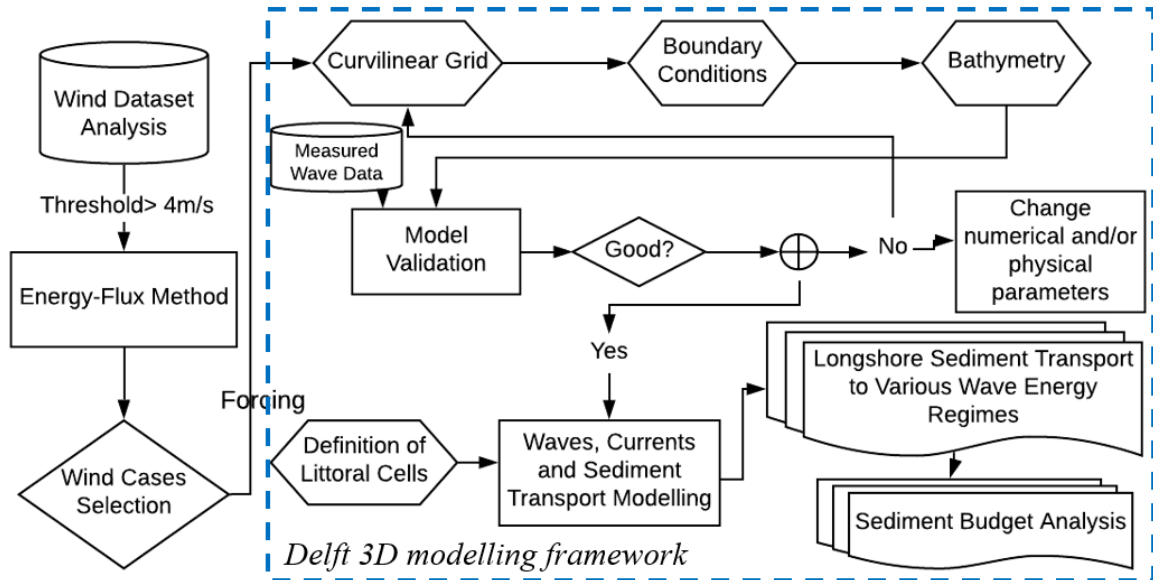


Figure 3. Methodology steps.

Numerical Model

A process-based numerical model (Delft 3D) was used to simulate wave generation and propagation, currents, and sediment transport at Lagoa dos Patos (Brazil). Delft 3D is composed of several integrated modules, which together allow the computation of wind and wave induced circulation and sediment transport. The short-wave generation, propagation, and dissipation are calculated by the fully spectral wave model SWAN - Simulating Waves Nearshore (Booij et al., 1999; Ris et al., 1999). Furthermore, Delft 3D-Flow simulates the hydrodynamic flow and sediment transport in complex situations (e.g.: flow acceleration, deceleration, and curvature, wind- and wave- driven currents) by an online coupling mode with the Delft 3D-Wave module (Lesser et al., 2004; Roelvink et al., 2001).

Grids and Bathymetry

The model domain covers an area of 246 x 68 km, and the Wave and Flow modules used a curvilinear computational grid, smoothly varying from 98 x 200 m near the spits, to 200 x 600 m further away. The bathymetric data is based on the Brazilian Navy Nautical Chart number 2140.

Waves

The mechanisms of wave generation, propagation and dissipation; including the linear and exponential wind growth (Komen et al. 1984), refraction due to depth and current variations, non-linear triad wave-wave interactions (Eldeberky and Battjes, 1995; Eldeberky, 1996), whitecapping (Westhuysen, 2007), bottom friction of JONSWAP ($C_b=0.038 \text{ m}^2 \text{ s}^{-3}$) (Hasselmann et al., 1973), and depth induced wave breaking (Battjes and Janssen, 1978) were computed.

The wave cases from which the sediment transport modeling was derived were defined by Miranda et al. (2020). The authors used an input reduction approach similar to the Energy-Flux Method (Benedet et al., 2016), in which, an hourly recorded wind dataset (see Figure 1 for meteorological station location) was divided into 9 classes of direction and 4 classes of magnitude, which resulted in 36 classes with the same frequency of occurrence (1.79%) (after filtering for wind speeds below 4 m/s – representing calm conditions within the lagoon water body, 64.56% of the total time). From which representative wind cases were calculated for each class. From the 36 cases, 27 cases capable of generating significant sediment transport were modeled (Figure 4).

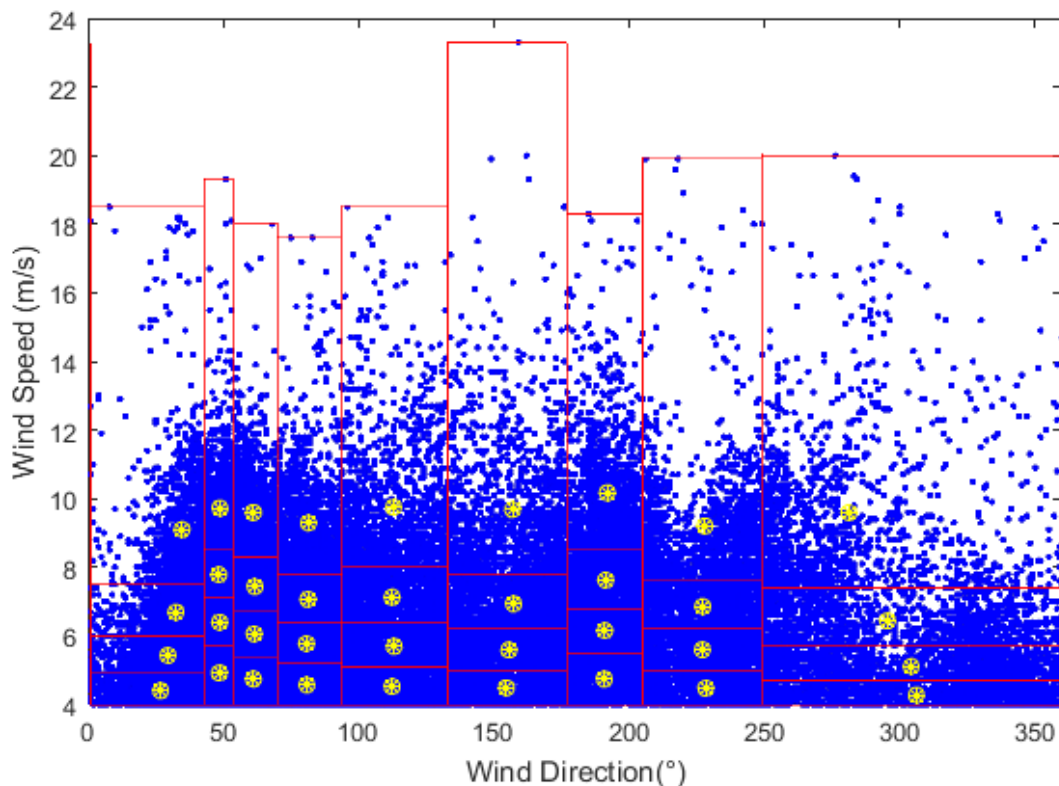


Figure 4. Input reduction method (similar to the Energy-Flux Method, Benedet et al. 2016) applied for the definition of the wind cases used as forcing conditions in the model. Source: modified from Miranda et al. (2020).

Flow

Two open boundaries were used in the FLOW module; one 1) At the mouth of Guaíba river (northwestern end of the lagoon) with a constant total discharge (988 m³/s), based on the study of Andrade Neto et al. (2012) and another; 2) near the lagoon inlet, where the tidal constituents (amplitude and phase) provided by Praticagem Rio Grande (Brazil) were imposed. The model was calibrated by Miranda et al. (2020) with measured wave data, and a good correlation between the modeled and measured wave parameters were obtained; from February to April 2015; RMSE Hs= 0.19 m, RMSE Tp =1.06 s, RMSE U= 0.19 and RMSE V= 0.18, with U and V components converted from wave direction and magnitude.

The Van Rijn (1993; 2000) sediment transport formulations were used for the computation of non-cohesive sediment transport (sand) with a median grain size (D_{50}) of 0.40 mm, based on the studies of Toldo (1994), Lemke (2015) and Oliveira et al. (2018).

The longshore sediment transport was computed for cross-sections extending from the shoreline until the 3 meters isobath (see Figure 1 for location). Sediment transport rates (m³/s) were converted to annual transport (multiplied by the number of seconds in a year and weighted by the frequency of occurrence of each individual case).

Littoral Sediment Budget

The estimation of the sediment budget was carried out using the regional sediment budget approach based on the principle of conservation of mass of the sediments (Rosati, 2005). To do so, the annual sediment transport rates were derived from each of the scenarios described previously and the average cases were also individually analyzed.

Continental sources were not considered because of interventions in water courses through the construction of dams to pump the water to rice fields. Sediment losses through the overwash process and the transport below the base of the shoreface were also not accounted for.

Littoral cells.

Four main sediment compartments were defined based on the general morphology of the coast: two lagoon bay beaches and three adjoining nearly symmetrical sandy spits. Then, each compartment was subdivided based on changes in shoreline orientation and beach topography (Table 1).

Along the subaqueous bars, four sub-cells were defined: i. Proximal (near the tip of the emerged spit), ii. Proximal-intermediary (the central portion) iii. Intermediary-distal (from the central portion of the bars to the distal portion), and iv. the subaqueous bars terminus (Table 1).

The onshore and offshore boundaries were defined between the shoreline and the depth of closure (calculated to be 3.3 m, Miranda et al., 2020).

Table 1. Defined sediment compartments (littoral cells), length (km), shoreline orientation (θ°), and shoreface width (km).

| Cells | Sub-cells | Shoreline orientation (θ°) | Length | Width (km) |
|---------------------------------|------------------|--|---------------|--------------------|
| Dona Helena spit | Spit-H1 | NW- SE ~129° | 2.0 km | 4.0 km |
| | Spit-H2 | | 5.0 km | 2.8 km |
| | Spit-H3 | | 6.0 km | 1.8 km |
| | Spit terminus | | 2.0 km | 1.3 km |
| Northern Bay Beach (NBB) | NBB 1 | S | 5 km | From 1.3 to 2.7 km |
| | NBB 2 | S | 1.7 km | 4.0 km |
| | NBB 3 | SE | 2.4 km | 4.5 km |
| | NBB 4 | SE | 2.6 km | 5.0 km |
| | NBB 5 | ESE | 3.1 km | 4.3 km |
| | NBB 6 | E | 3.6 km | 3.7 km |
| | NBB 7 | E | 3.4 km | 1.0 km |
| | NBB 8 | ENE | 4.1 km | 0.77 km |
| | NBB 9 | ENE | 3.5 km | 1.3 km |
| | NBB 10 | ENE | 5.15 km | From 1.2 to 1.7 km |
| Dona Maria spit | Spit-M1 | NW-SE ~133° | 4.3 km | 7.7 km |
| | Spit-M2 | | 7.8 km | 3.8 km |
| | Spit-M3 | | 7.6 km | 2.9 km |
| | Spit terminus | | 3.2 km | 2.2 km |
| Southern Bay Beach (SBB) | SBB 11 | SSE | 6.0 km | 6.0 km |
| | SBB 12 | SSE | 2.7 km | 6.4 km |
| | SBB 13 | SSW | 1.7 km | 7.7 km |
| | SBB 14 | SE | 1.7 km | 7.6 km |
| | SBB 15 | S | 3.9 km | 7.9 km |
| | SBB 16 | SSE | 3.5 km | 5.2 km |
| | SBB 17 | ESE | 3.9 km | 2.5 km |
| | SBB 18 | E | 4.9 | 1.8 km |
| | SBB 19 | E | 5.3 | From 1.2 to 1.7 km |
| Vitoriano spit | Spit-V1 | NW-SE ~136° | 2.8 km | 7.1 km |
| | Spit-V2 | | 6.9 km | From 5.9 to 3.5 km |
| | Spit-V3 | | 6.8 km | 2.5 km |
| | Spit terminus | | 3.7 km | 3.3 km |

RESULTS

The following sections present the potential longshore drift and the regional sediment budget of the area. Sediment sources, transport pathways, storages, and sinks are identified and described.

Longshore Transport Patterns (LST) on Large Lagoon Bay Beaches.

The northern protected coastal segments of both bay beaches show almost no sediment transport under wave fields of moderate energy from the NNE to the E directions due to the sheltering provided by the northern spits (Figure 5a-d, j-m).

Under high energy NE-E wave fields, the northern coastal segments of the southern bay beach (SBB) present high longshore sediment transport rates (up to $720 \text{ m}^3\text{y}^{-1}$) to the south (Figure 6k-m). This region is marked by a larger width and smooth gradient of the shoreface in comparison to the NBB (Figure 6b-d).

In the north-central (semi-protected) sector of the beaches, sediment is transported to the south, towards the central beach section, under high energy NE and ENE waves (up to $300 \text{ m}^3\text{y}^{-1}$ in the NBB and up to $930 \text{ m}^3\text{y}^{-1}$ in the SBB) (Figure 6b-c, k-l). A subsequent decrease in the LST rates occurs in the central beach section, following the accentuated narrowing in the shoreface width and smaller rates are observed in the narrowest beach section - up to $20 \text{ m}^3\text{y}^{-1}$ in the NBB and up to $160 \text{ m}^3\text{y}^{-1}$ in the SBB (Figure 6bc, cross-section 8; Figure 6kl, cross-sections 18-19).

The southern coastal segments (the updrift coast of the spits), in turn, present an abrupt increase in LST rates under the action of the NE-E wave fields of moderate (up to $300 \text{ m}^3 \text{y}^{-1}$, Figure 5) and high energy (up to $1,300 \text{ m}^3 \text{y}^{-1}$, Figure 6). From this sector, sediment is transported towards the subaqueous bars until their distal ends, but more than half of the sediment load is deposited in the proximal region of Dona Maria spit (Spit-M1) and the central region of Vitoriano spit (Spit-V2) (Figure 7).

Moderate and high energy S-SSW wave fields generate northerly sediment transport from the center towards the northern sector of the northern bay beach, at higher rates nearby Arambaré city (up to $280 \text{ m}^3 \text{y}^{-1}$), and deliver the majority of the sediments to the southern tip of Dona Helena spit (Figure 6g, see Figure 1 for cross-sections location). While in the south bay beach sediment is transported from the northern and southern beach ends towards the center of the beach, and opposite transport directions are observed below 3 m depth, showing that in this case sediment is transported offshore from the convergent nodal point and redirected, characterizing a cell type circulation (Figure 6p).

Sediment exchange also occurs between the proximal portion of the subaqueous bars and the downdrift beaches. It occurs in the NBB under the high energy SW wave field (up to $170 \text{ m}^3 \text{y}^{-1}$) (Figure 6h, cross-section 1) and in the SBB under the high energy SSE, S-SSW and SW wave fields (up to $360 \text{ m}^3 \text{y}^{-1}$) (Figure 6o-q, cross-section 12).

Moreover, reversals in the sediment transport directions occur on the leeward side of Dona Helena (northern end of NBB) and Dona Maria (northern end of SBB) spits, in which sediment is transported from the northern sector of the beaches (NBB and SBB) toward the northern spits (Dona Helena and Dona Maria, respectively) (Figure 5e-f; Figure 6b-f, k-n).

Complex sediment transport patterns are observed for the wave fields which propagate nearly across the transversal axis of the lagoon, and to which the lagoon bay beaches are most exposed, showing the development of convergent and divergent nodal zones (Figure 5e,f,o, Figure 6d-f, m-p).

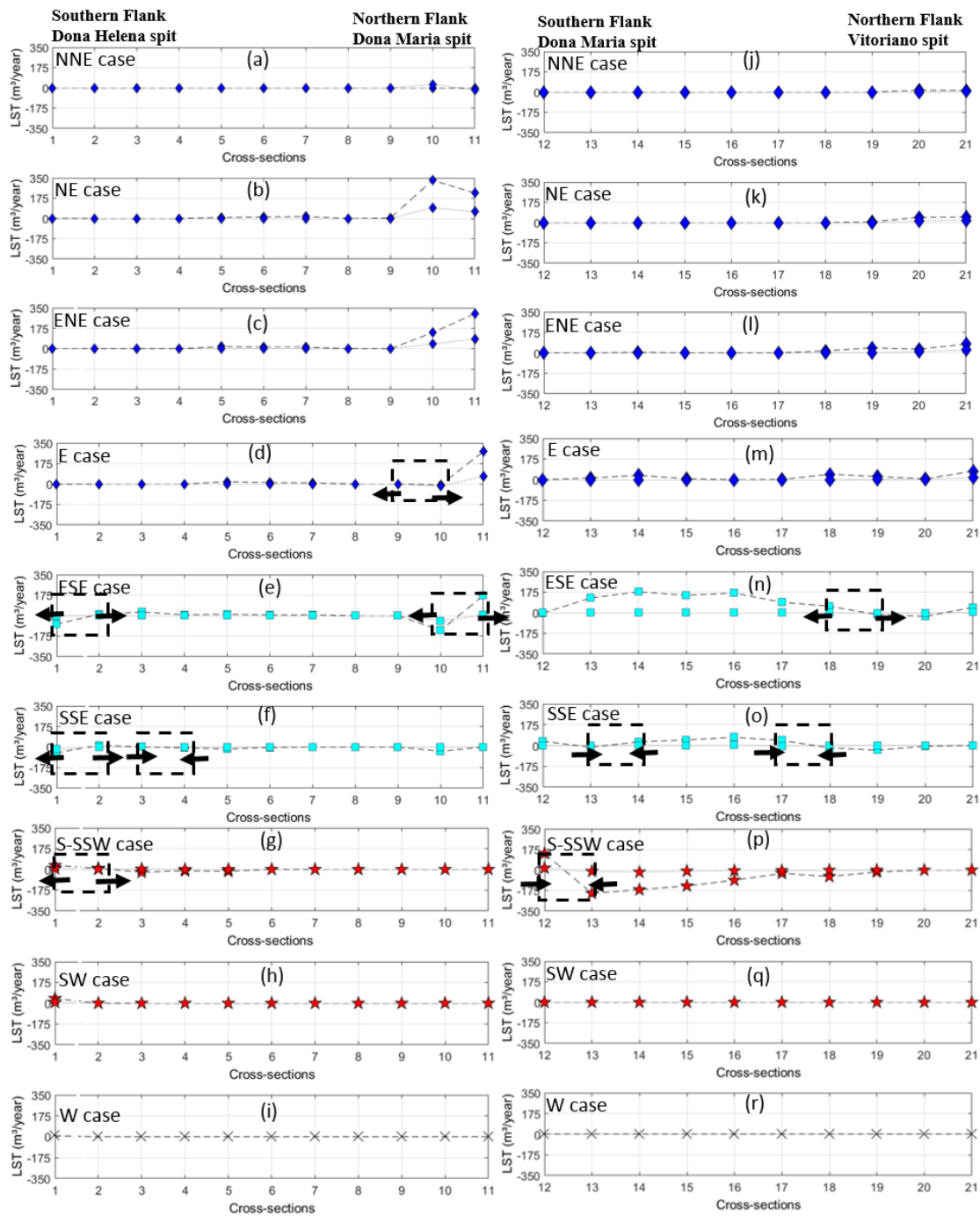


Figure 5. Potential longshore sediment transport rates along the northern (left side) and southern (right side) bay beaches, under moderate wave energy conditions. The positive values indicate southerly sediment transport, while the negative values indicate northerly transport. (For cross-section locations please refer to Figure 1).

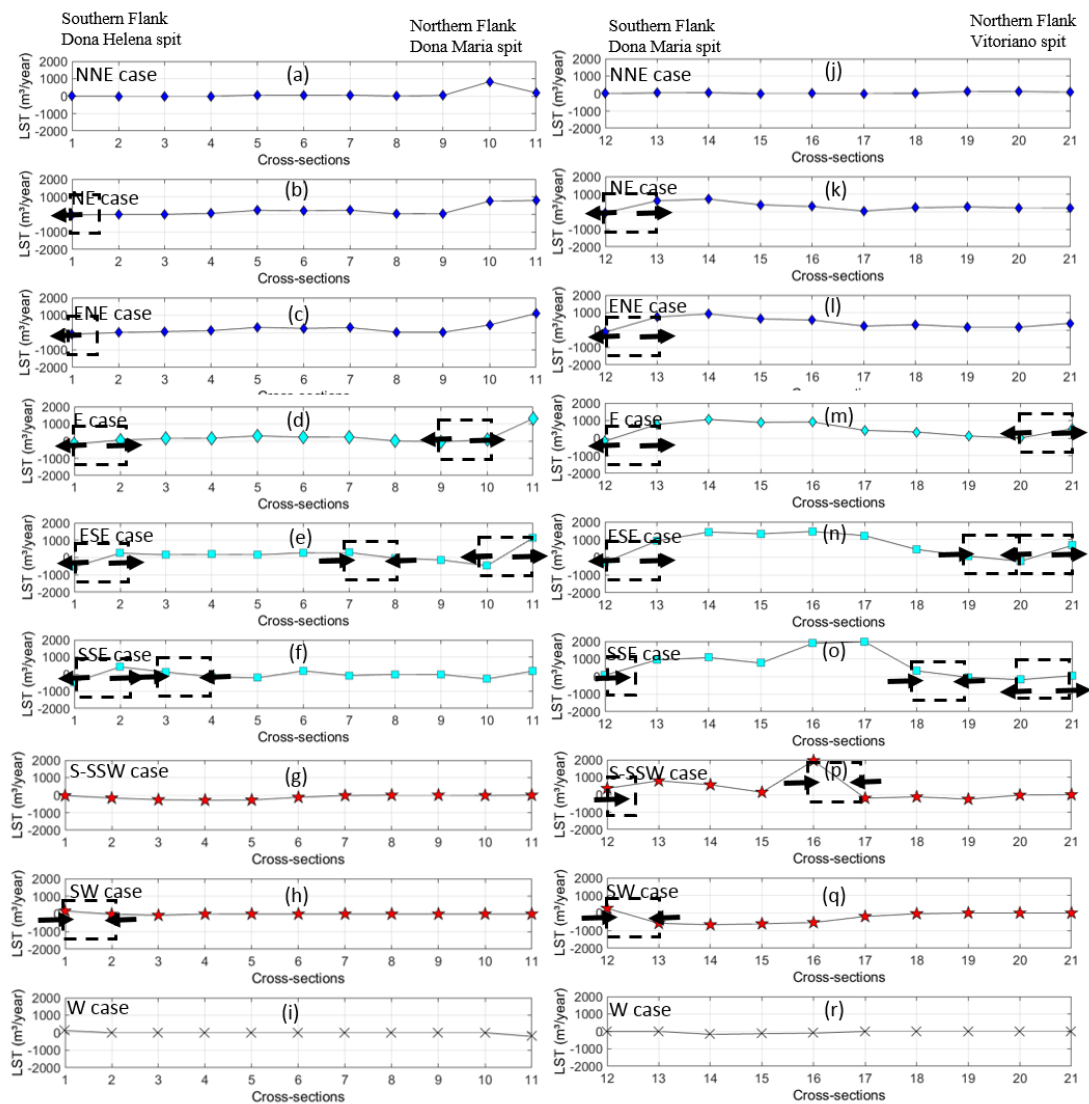


Figure 6. Potential longshore sediment transport rates along the northern (left side) and southern (right side) bay beaches, under extreme wave conditions. The positive values indicate southerly sediment transport, while the negative values indicate northerly transport. (See Figure 1 for cross-sections locations, from 1 to 11 in the northern bay beach, and 12-21 in the southern bay beach).

Littoral Sediment Budget

From the results presented above, the sand budget of this part of the lagoon has been derived. Figure 7 shows the regional sediment budget for each cell of the analyzed rhythmic lagoon coastline. The results correspond to the integration of the sediment transport from all wave cases (weighted by their frequency of occurrence) and are presented in $\text{m}^3 \text{y}^{-1}$.

The results presented here demonstrate the role of the spits in sheltering the coast to different wave directions and the control of the configuration of the coastline to the sediment budget of the area. A pattern of inter-related source and storage areas was observed along the coastal segments (Figure 7). The northern coastal segments of both bay beaches presented a net deficit. Those sectors have few sources of sediments (i.e.: the proximal cell of the northern

subaqueous bars under specific wave conditions); also, sediment divergent nodal zones develop in this region under high energy ESE and SSE wave fields, being source of sediments to the downdrift beach and to the northern spits (Figure 5; Figure 6).

Subsequently, a net surplus is observed in the indented sections of the shoreline (e.g. the inflection point of the coast in the northern bay beach - NBB2, and in the convex sector of the coast of the southern bay beach - SBB13). Another potential sediment deficit zone occurs in the semi-protected sectors of the bay beaches (NBB4; SBB14), which were identified as sources of sediment to the central beach section.

The central cells of the beaches (NBB7 and SBB15, SBB16), in turn, present a net surplus due to the accumulation of sediments mainly transported by the NE, ENE and E high energy waves from the semi-protected coastal segments. Also, by the sedimentary convergence on the northern bay beach under high energy ESE waves, and on the southern bay beach under ESE, SSE, and S-SSW high wave energy conditions.

The southern cells of both bay beaches (the updrift coast of the spits), were identified as the main sources of sediments to the subaqueous bars (Figure 7), even for modest volumes under moderate wave energy conditions (see Figure 5).

The distal portion of the subaqueous bars mainly behave as a sediment sink (Figure 7, Spit-H3, Sspit-M3, Spit-V3), especially for the northern spit (Dona Helena), which is subjected to the direct attack of the predominant NE and ENE waves. Those wavefields are especially responsible for the great amounts of sediments transported towards the southern flank of the bars (Figure 7).

The proximal region of the subaqueous bar of Dona Maria behaves as a sediment storage, as the majority of the sediment load is deposited in this sector (Spit-M1), and less sediment is gained towards the distal part of the bar (Spit-M2-M3) (Figure 7).

The proximal region of the subaqueous bar of Vitoriano, in turn, presented a net deficit (Spit-V1), providing sediment to the distal portion of the bar and also to the emerged spit under the SW and W wave action.

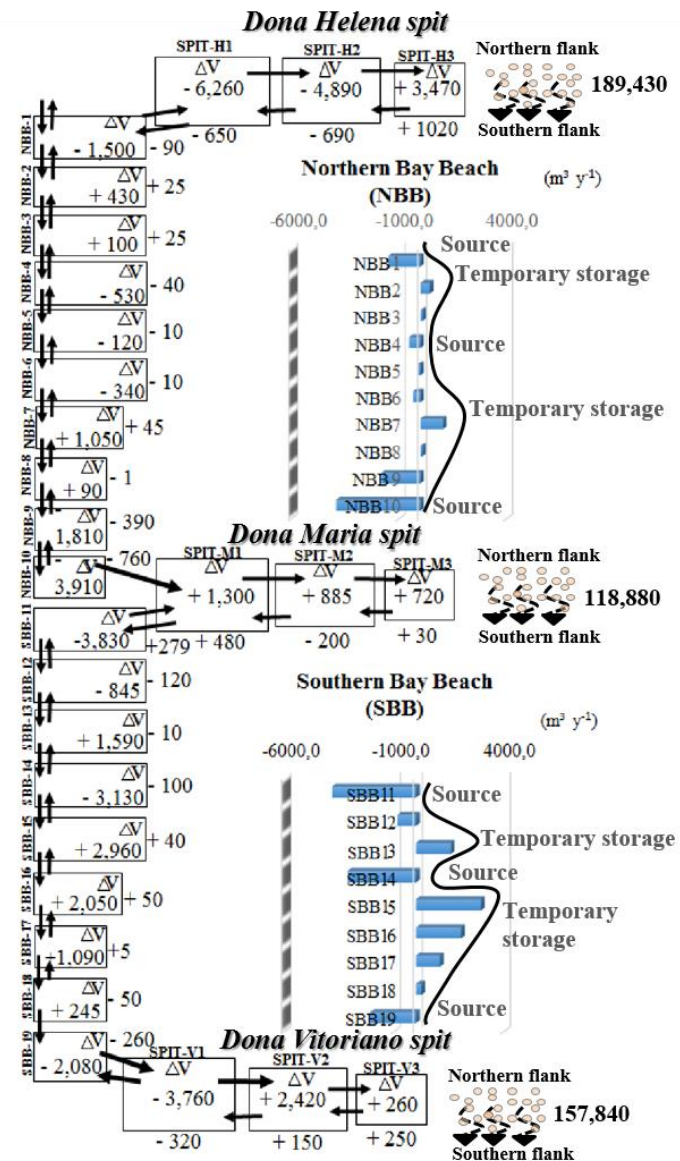
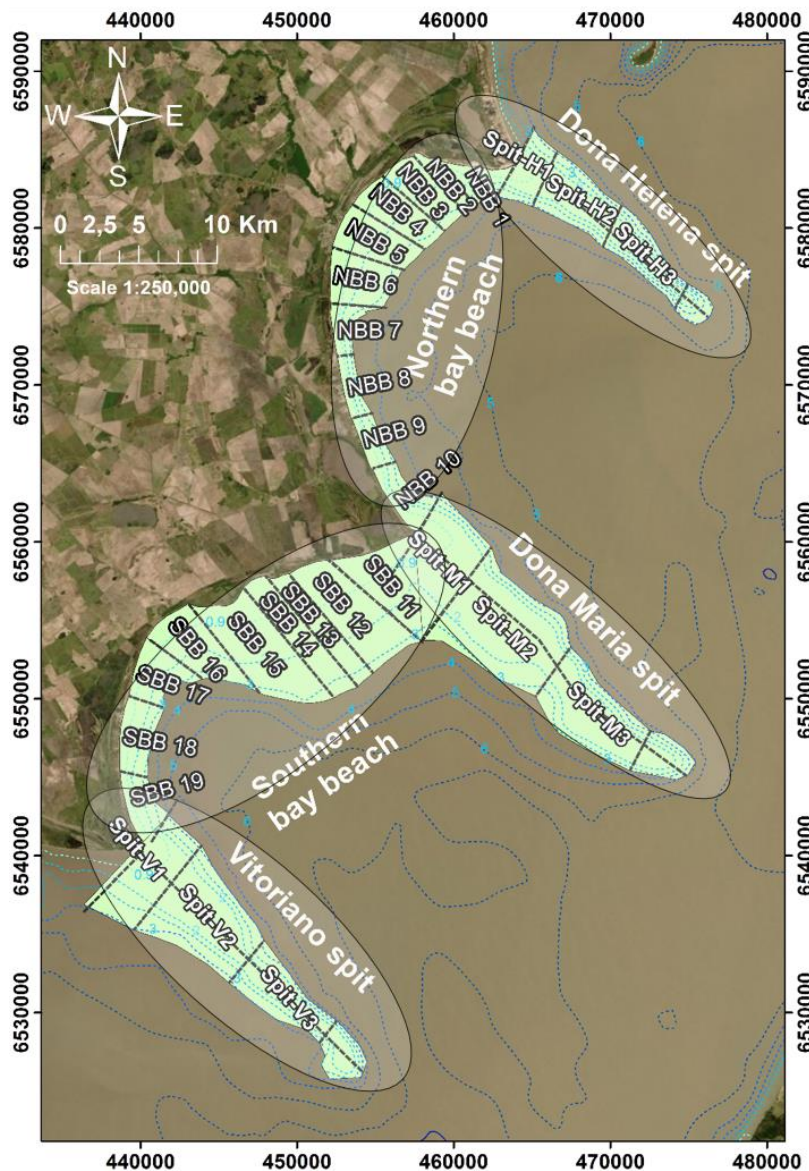


Figure 7. Potential sediment budget by littoral drift rates ($\text{m}^3 \text{y}^{-1}$) per littoral cell (For details see table 1). The box results are also illustrated by the graph bars, demonstrating the pattern of inter-related negative and positive sediment budgets along both bay beaches. Values outside the box correspond to the budget derived from the transported material induced by the wave-flux from the intermediate wave cases. The map on the left side indicate the sediment compartments marked by circles, and the littoral cells defined for the sediment budget analysis.

Image Source: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, the National Centre for Space Studies (CNES)/Airbus DS, U.S. Department of Agriculture, U.S. Geological

DISCUSSION

The net transport to the south along the bay beaches is in agreement with Toldo et al.'s (2003) study, which showed the dominance of southward longshore currents generated by prevailing NE and ENE waves on the lagoon's west margin. Intense northward transport is also observed under SSE (in the NBB), S-SSW, and SW wave fields (up to $290 \text{ m}^3 \text{ y}^{-1}$ in the NBB and to $660 \text{ m}^3 \text{ y}^{-1}$ in the SBB), which is associated with stormy wind conditions in the region. Thus, characterizing a bi-directional sediment transport pattern with a net transport to the south.

The wave sheltering generated by the spits plays an important role on sediment transport within the lagoon. The larger wave shadow zones formed under the action of the moderate NNE-E wavefields (Miranda et al. 2020) agrees with the almost absent sediment transport in the northern coastal sectors of the beaches for these scenarios (Figure 5), with a larger shadow zone region for the southern bay beach due to the larger dimension of the central spit.

The NE, ENE and E wave cases generate similar LST patterns in the lagoon bay beaches; the sediment transport is almost absent in the northern coastal segments of the beaches under the moderate NNE-E wavefields, while an increase in the transport rates occurs in the southern coastal segments – the updrift coast of the spits (Figure 5; Figure 6). This similarity is explained by the similar alongshore spatial distribution of the incident wavefield characteristics, with the formation of wave shadow zones on the upcoast of the bay beaches by the presence of the spits and an increasing wave energy gradient towards the south (Miranda et al. 2020).

The aforementioned scenario confirms studies conducted by laboratory experiments, which shows that in the wave shadow zone the sediment transport is considerably reduced while it is intensified at the spits edge (Uda et al. 2014). An exception to this statement is observed in the southern bay beach under high energy NE-E wave fields, in which higher sediment transport rates occur in the northern sector of the beach (Figure 6k-m) due to the formation of sub-areas of local wave generation (Miranda et al. 2020), and the wider and smoother shoreface morphology in this region (see Figure 1).

Differences in the littoral drift patterns also occur between the two bay beaches under the same wave condition because of site specific controls, such as the different degrees of coastline exposure and the variability in the shoreface morphology, demonstrating the importance of site specific controls on coastal processes at different local levels (Jackson and Nordstrom, 1992; Vieira da Silva et al., 2018; Miranda et al., 2020).

The cusped spits in Lagoa dos Patos (BR) are analogous to the cusped features of North Carolina (USA). As highlighted by Carter (1988), the processes found on coasts of lakes and

lagoons are similar to the processes found on the ocean coast. This similarity can be observed between the cusped spits of Lagoa dos Patos and the cusped foreland of Cape Lookout (North Carolina, EUA) studied by McNinch and Wells (1999) and Park and Wells (2005). For both cases it can be seen that; (i) the updrift cells of the emerged cusped features are the main sources of sediments to its submerged portion (ii) the cusped features limit the sediment bypassing between the adjacent beaches, (iii) the proximal cell of the subaqueous bars are source of sediment to the downdrift beaches under specific wave conditions and, (iv) sediment transport reversals occur on the leeward side of the emerged spits or capes.

The regional sediment budget analysis revealed the existence of inter-related source and storage areas along both bay beaches (see Figure 7). The cells on the northern end of the lagoon bay beaches (NBB1, SBB11, SBB12) and in the semi-protected sector (NBB3, NBB4, SBB14) were identified as sediment sources. The divergent nodal zones in the northern end of the beaches, and the prevailing occurrence of oblique wave incidence in the semi-protected sector were identified as causes of this sediment deficit, respectively, which agrees with the shoreline retraction observed at inter-annual periods by Miranda et al. (2019). However, it is important to highlight that in the medium-term a tendency toward shoreline progradation is observed (Miranda et al. *op cit*).

Sediment accumulation also occurs in the northern and southern edges of the emerged spits as evidenced by the growth of beach ridges in the southern flank of Dona Maria spit (Figure 2f), and northern flank of Vitoriano spit (Figure 2g). Thus, the emerged spits also act as sediment sinks despite the majority of the sediment load being deposited in the proximal region of the subaqueous bar of Dona Maria (Spit-M1) and the central region of the subaqueous bar of Vitoriano (Spit-V2).

Regions with highly indented shapes of the shoreline, where convergent nodal zones occur (NBB-2) and where an accumulation of sediment occurs due to the decrease in the angle of wave-approach (in the convex shape of the shoreline, SBB-13, SBB-15), show a positive sediment budget.

The central coastal segment of the lagoon bay beaches were identified as temporary storage areas (see Figure 7, NBB7, SBB15, SBB-16), due to the accumulation of sediments under the NE, ENE and E wave regimes (Figure 6, cross-sections 7-8, cross-sections 16-18) because of changes in the shoreline alignment and the resultant decrease in the angle of wave-approach. This is a similar process to the sediment accumulation observed in indented shapes on the sinuous coast of the adjacent ocean shore (CPRS) (Toldo et al. 2006b). This region is

also marked by an accentuated narrowing of the shoreface width, increasing the wave refraction effect (Miranda et al., 2020). Moreover, the convergent sediment nodal zones developed under the ESE and SSE wave fields on both bay beaches; and under the S-SSW wave field on the southern bay beach also contribute to the positive sediment budget of these coastal segments.

As aforementioned, the sediment budget of the southern littoral cells of the bay beaches (the updrift coast of the spits) is directly coupled to the subaqueous bars, similar to the cusplate system of Cape Lookout (McNinch and Wells, 1999; Park and Wells, 2005).

Park and Wells (2005) used the average value of the longshore sediment transport rates at the southern compartments of Core Banks (updrift coast of the shoal) to estimate the annual sediment input to the shoal ($512,000 \text{ m}^3 \text{ y}^{-1}$). By using a similar approach, it was estimated that there is an annual sediment input to Dona Maria spit on the order of $2,900 \text{ m}^3 \text{ y}^{-1}$, and of $900 \text{ m}^3 \text{ y}^{-1}$ to Vitoriano spit. The reduced sediment input to the Vitoriano spit agrees with the sediment starvation of the feature referred to in the previous work of Miranda et al. (2019), in which the cannibalization (recycling) of the subaqueous bars result in the up-building of sandbanks, followed by its landward migration - a superimposed process to the long-term tendency of the feature.

Zenkovitch (1959) highlighted the increased role of the wave fields propagating across the short lagoon axis on the final stages of development of an elongated lagoon due to the increased wave fetch. Miranda et al. (2020) complemented attesting the minor influence of the lagoon cusplate spits in these wave fields (by wave sheltering and attenuation). Here, complex sediment transport patterns were observed for the wave fields propagating across the short lagoon axis, with the development of both convergent and divergent nodal zones in the longshore sediment transport. Moreover, the nodal zones are also seen to exert an important influence on the regional sediment budget; i. Coastal segments with negative sediment budget where divergent nodal zones occurs, and ii. Coastal segments with positive sediment budget on convergent nodal zones.

Finally, the budget can be considered unbalanced, thus not providing enough sediments for the present day to maintain the subaqueous bars emerged.

CONCLUSION

The present paper aimed to quantify the sediment budget of the cusplate coast of Lagoa dos Patos and analyze its influence on cusplate spit development, while also identifying the main longshore sediment transport patterns and investigate the controlling factors.

Summarizing, the rhythmic western lagoon cusped coast presents a net sediment transport to the south in accordance with the growth direction of the geomorphological features, confirming previous studies.

The regional sediment budget analysis shows a potential pattern of negative and positive budgets of inter-related littoral cells along the bay beaches due to variations in the alongshore wave energy gradients and changes in the angle of incidence on the highly indented shapes of the shoreline.

The cusped features limit the sediment exchange between the adjacent beaches. However, under specific wave conditions, the proximal cells (near shore) of the subaqueous bars provide sediments to the downdrift beaches.

Convergent and divergent nodal zones were identified, which showed an important influence on the regional sediment budget.

The northern semi-protected sectors of bay beaches are sources of sediments to the center portion of the beach, where an accumulation of sediments occurs under the NNE-E wave action (including the predominant NE and ENE waves) due to changes in the shoreline alignment and variations in the shoreface width, while the sediment budget of the southern coastal segments –the updrift coast of the spits- is directly coupled with the subaqueous bars, being its greatest source of sediments, even during moderate wave energy states.

Ultimately, the shoreline orientation and the shoreface morphological characteristics, allied to the cusped spits' influence on waves, are important factors on the control of the longshore sediment transport patterns within the bays, which controls the amounts of sediments supplied to the spits and thus, further morphological changes. In the Vitoriano spit case, the reduced sediment input to the spit resulted in an adaptive response of the feature in which the depositional signal is due to an autogenic behavior of the system.

Also, it is recommended that future studies on the cross-transport be undertaken, especially to account for the sediment losses by the overwashing process over the updrift cells in the edges of the emerged spits.

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CAPÍTULO 6. CONSIDERAÇÕES FINAIS

A presente Tese de Doutorado teve como objetivo principal analisar o suprimento sedimentar para os esporões, e descrever e quantificar os processos morfodinâmicos e hidrodinâmicos que operam na evolução morfológica dos esporões arenosos rítmicos e arcos praias associados (feições rítmicas de larga escala da linha de costa) presentes na margem central oeste da Lagoa dos Patos, em escala de evento à escala histórica.

Para tanto, inicialmente, o terceiro capítulo da Tese (que trata do **objetivo específico A, 1ª questão**) analisa as mudanças na posição da linha de costa em escala de evento (interanual) à escala histórica (décadas), utilizando técnicas de geoprocessamento e com o emprego dos métodos DSAS e do Método do Polígono de Mudança.

A análise das mudanças costeiras em escala histórica (décadas), entre os anos de 1984 e 2013, demonstrou que os arcos praias apresentam um comportamento predominantemente estável na posição da linha de costa, sendo que 60% do trecho costeiro do arco praias norte (Arambaré) e 74% do trecho costeiro do arco praias sul apresentaram valores estáveis, associado a uma baixa taxa média anual geral de mudança costeira de +0,7 m/ano, dentro do valor de incerteza ($\pm 1,05$ m/ano), para ambos os métodos empregados (DSAS e Método do Polígono de Mudança).

Em contrapartida, na análise de menor escala espaço temporal (interanual), foi identificada a existência de fases alternadas com predominante ocorrência de taxas de retração, progradação e estabilidade da linha de costa dos arcos praias, demonstrando o comportamento cíclico da linha de costa em períodos interanuais.

Outro importante fato a ser observado foi a agração e emersão de barras arenosas sob os esporões submersos, e a subsequente migração em direção ao continente, acoplando-se à linha de costa do esporão emerso (processo superimposto à tendência de longo prazo da feição).

No capítulo 4 (**objetivos B e C**), foi demonstrado que a configuração da linha de costa cuspidada (orientação da linha de costa e morfologia submersa) influencia (1) no padrão de propagação das ondas, assim como (2) na atenuação de ondas geradas por casos de vento de elevada magnitude ($> 9,0$ m/s) no interior da Lagoa dos Patos, resultando em padrões regionais de gradação lateral na energia das ondas incidentes nas margens lagunares para campos de onda de diferentes direções, especialmente os que se propagam ao longo do eixo lagunar com maior comprimento no campo de atuação dos ventos (“*fetch*”) (longitudinal).

Respondendo à **2ª pergunta de pesquisa**, tem-se que os esporões emersos e submersos, juntamente com a orientação da linha de costa, exercem importante controle nos campos de ondas da Lagoa dos Patos através dos processos de (1) sombreamento de onda, decorrente da presença dos esporões emersos, (2) e pelas transformações de ondas em águas rasas, em especial os processos de refração e os mecanismos de dissipação das ondas na passagem pelo extenso banco submerso raso dos esporões, influenciando na distribuição espacial das características das ondas incidentes ao longo das margens lagunares [especificamente a energia (W/m) e os ângulos de incidência de onda com relação à costa ($\varphi-\theta$)].

Os controles exercidos pelos esporões arenosos, em conjunto com a configuração dos arcos praias, ocasionam semelhantes distribuições longitudinais de energia e ângulos de incidência de ondas para diferentes direções de geração de ondas, em especial para os campos de ondas que se propagam ao longo do eixo lagunar com maior comprimento da pista de vento (NNE, NE, ENE, E, S-SSW e SW). Para os quais observam-se (i) o desenvolvimento de zonas de sombra a sotamar do esporão, variando em extensão de acordo com a projeção (dimensão) e orientação do esporão emerso, e a direção da onda incidente; (ii) semelhante distribuição longitudinal de energia das ondas incidentes (W/m), aumentando em direção ao setor sul dos arcos praias para as ondas de NNE, NE, ENE e E, e em direção ao setor norte para as ondas de SW e S-SSW; (iii) e semelhante distribuição longitudinal dos ângulos de incidência de ondas com relação à orientação da linha de costa dos arcos praias, destacando-se que (à semelhança das ondas predominantes) todas as direções de campos de ondas supracitadas, apresentam elevada obliquidade de incidência de onda restrita ao setor semiabrigado da costa, onde o prisma praias submerso apresenta maior largura e gradiente mais suave.

Tais ajustes entre a hidrodinâmica e a configuração morfológica da costa promovem maior efetividade na diminuição do poder erosivo das ondas, por dissipação ou pela associação de ondas de elevada energia (W/m) com baixos ângulos de incidência ($\varphi-\theta$), em especial para os campos de onda que possuem maior comprimento da pista de vento, os quais são assumidos como os principais agentes promotores das mudanças morfológicas das margens de lagunas costeiras alongadas.

Com relação à **3ª pergunta de pesquisa**, constatou-se que os esporões submersos são responsáveis por representativa atenuação da altura de onda no interior da Lagoa dos Patos, com elevada variabilidade (18% a 46%) ao longo das diferentes porções longitudinais dos esporões (i. raiz /ou região próxima à costa; ii. centro; iii. porção distal, próximo a sua terminação).

A elevada variabilidade na atenuação de onda ao longo dos esporões (com taxas variando entre 18 % à 46 %) é associada à variável morfologia da feição, e ao controle que a geometria (*fetch*) e a profundidade da bacia exercem na geração de ondas e, conseqüentemente, nas características das ondas incidentes (H_s e T_p) nas diferentes porções dos esporões (Tabela 4, cap.4.).

Em particular, as ondas predominantes (NE e ENE) apresentam elevado grau de atenuação na passagem pelas regiões proximais e centrais da porção submersa dos esporões Dona Helena (norte) e Dona Maria (central), variando entre 39% e 46%, reduzindo assim a energia de onda transmitida para os setores praias a sotamar dos mesmos.

O capítulo 5 fornece resultados quantitativos que demonstram a importância do controle exercido pela configuração da linha de costa e a associada variabilidade na morfologia da antepraia nos padrões de transporte sedimentar longitudinal para campos de ondas gerados por casos representativos de ventos de diferentes direções e magnitudes, assim como foram identificadas áreas fontes e receptoras de sedimentos ao longo da costa, permitindo a proposição de um modelo conceitual de balanço regional de sedimentos para a costa cuspidada “*cuspedate shoreline*” em questão.

Atendendo ao **objetivo específico D e respondendo à 4ª pergunta de pesquisa**, identificou-se a existência de um padrão bidirecional na deriva litorânea de sedimentos, com transporte líquido para sul, concordante com a direção de crescimentos dos esporões, e corroborando os estudos prévios.

O setor norte dos arcos praias praticamente não apresenta transporte sedimentar sob a ação dos campos de onda de NE-E de moderada energia, devido à formação de uma zona de sombra a sotamar dos esporões, com maior área de extensão para o arco praias sul, devido à maior dimensão do esporão Dona Maria. Contudo, para os casos extremos de campos de ondas de NE-E, o setor norte do arco praias sul apresenta elevadas taxas de transporte sedimentar para sul (podendo atingir uma taxa máxima de 720 m³/ano em uma região marcada por extensa largura e suave gradiente do prisma praias submerso), devido ao estabelecimento de uma sub-área de geração de ondas locais.

No setor norte-central (semiabrigado) dos arcos praias, é observado transporte sedimentar para sul sob a ação dos campos de ondas de NE-E (podendo atingir uma taxa de até 300 m³/ano no arco praias norte e 930 m³/ano no arco praias sul em condições extremas), com a redução dos fluxos sedimentares no setor central dos arcos praias, devido à diminuição no ângulo de incidência de onda com relação à costa ($\varphi-\theta$), associada com a mudança na orientação

da linha de costa (Figura 7 – Cap. 4), o que acarreta em elevada acumulação de sedimentos neste setor. Já no setor extremo sul dos arcos praiais, região a montante dos esporões submersos, ocorre um elevado aumento na magnitude das taxas de transporte sedimentar para os campos de ondas de NE, ENE e E, atingindo um valor máximo de 1.303 m³/ano para o caso extremo de onda de E. Deste setor, os sedimentos continuam sendo transportados até a porção distal dos esporões submersos.

Intenso transporte sedimentar para norte também ocorre em ambos os arcos praiais, sob a ação dos campos de ondas de SSE (no arco praiial norte), S-SSW e SW em ambos os arcos praiais, podendo atingir 290 m³/ano nas proximidades do balneário de Arambaré em condições extremas, o que está associado à incidência de ondas oblíquas de elevada energia.

Notavelmente, zonas nodais de divergência e convergência na deriva litorânea de sedimentos foram identificadas ao longo dos arcos praiais, especialmente para os campos de ondas que se propagam ao longo do eixo transversal do corpo lagunar (ESE, SSE, S-SSW), para quais os arcos praiais encontram-se mais expostos. Inversões no transporte sedimentar ocorrem a sotamar dos esporões emersos (setor extremo norte dos arcos praiais) e, zonas de convergência sedimentar ocorrem no setor central dos arcos praiais, com a migração do ponto nodal dependendo da direção do campo de onda.

Ressalta-se, também, que fatores condicionais locais, como a exposição costeira e a morfologia do prisma praiial submerso, influenciam diretamente nos padrões de transporte sedimentar litorâneo nos arcos praiais, o que exerce um importante controle na taxa de suprimento de sedimentos para os esporões.

Ademais, trocas sedimentares ocorrem entre a raiz do esporão submerso e o setor costeiro ao sul do mesmo “*downdrift*” (setor norte dos arcos praiais); em específico, sob condições de ondas de SW, ocorre transporte sedimentar da porção submersa do esporão Dona Helena para o arco praiial de Arambaré e, sob condições de onda de SSE, S-SSW e SW, ocorre transporte do esporão Dona Maria para o arco praiial sul – apesar de, os esporões limitarem a transposição sedimentar entre as praias adjacentes, devido à projeção do esporão e ao banco submerso associado, responsável pela atenuação do processo de refração-difração na extremidade do esporão emerso.

O modelo conceitual de balanço regional de sedimentos (**objetivo específico D, respondendo à 5ª questão**) demonstrou um padrão na distribuição longitudinal das células litorâneas, intercambiando entre células com balanço negativo e positivo de sedimentos.

As células litorâneas no extremo norte dos arcos praias (NBB1, SBB2, SBB3, Figura 7, cap. 5) apresentaram um balanço negativo de sedimentos, porquanto que apresentam poucas fontes de sedimentos (por exemplo, a região proximal dos esporões submersos sob condições específicas de onda), além de ocorrerem zonas de divergência sedimentar neste setor sob a ação dos campos de ondas de E, ESE e SSE, constituindo-se em área fonte de sedimentos para os subsequentes segmentos costeiros ao sul, assim como para os esporões submersos ao norte (Figuras 5 e 6, cap. 5).

Subsequentemente, um balanço positivo de sedimentos ocorre nos setores costeiros com indentações na linha de costa (por exemplo, na acentuada inflexão na linha de costa do arco praias norte na célula NBB2, e no setor convexo da linha de costa no arco praias sul SBB13), ao passo que os seguintes segmentos costeiros (setor semiabrigado da costa) apresentam balanço negativo de sedimentos (NBB4, SBB14, Figura 7, cap. 5), devido à predominante incidência de ondas oblíquas nessa região (Figura 7, cap.4), constituindo-se em áreas fonte de sedimentos para o setores centrais dos arcos praias.

As células centrais dos arcos praias, por sua vez, constituem-se em áreas de armazenamento temporário, devido ao engarrafamento de sedimentos provenientes do setor semiabrigado da costa e devido à convergência na deriva litorânea de sedimentos nesse setor para determinados campos de ondas, conforme supracitado.

Os segmentos costeiros a barlar dos esporões emersos (setor sul dos arcos praias) foram identificados como as células litorâneas fontes de sedimentos para os esporões submersos, mesmo sob condições moderadas de energia de ondas.

A porção distal de todos esporões submersos atua como sumidouro de sedimentos, especialmente o esporão mais setentrional (Dona Helena), que está sujeito à incidência direta das ondas predominantes de NE e ENE. Tais campos de ondas são responsáveis por elevados volumes de transporte sedimentar para o flanco sul dos esporões submersos (Figura 7, cap. 5) e para regiões mais profundas que também constituem-se em sumidouros de sedimentos.

A região proximal do esporão Dona Maria comporta-se principalmente como área receptora de sedimentos (Spit-M1, Figura 7, cap. 5), e o aporte sedimentar diminui para as porções mais distais do esporão (Spit-M2, Spit-M3, Figura 7, cap. 5). Enquanto que a região proximal do esporão do Vitoriano atua principalmente como fonte (Spit-V1, Figura7, cap.5), fornecendo sedimentos para as praias lagunares e para regiões mais profundas do próprio esporão submerso (Spit-V2, Spit-V3, Figura 7, cap.5).

As zonas nodais de convergência e divergência na deriva litorânea também demonstraram exercer importante controle no balanço de sedimentos da costa, com balanço negativo em zonas de divergência sedimentar e balanço positivo em zonas de convergência sedimentar.

Com respeito à **6ª pergunta de pesquisa**, entende-se que o sistema praiial analisado apresenta um elevado grau de estabilidade processual, destacando-se: 1. as baixas taxas de variação na posição da linha de costa em escala histórica; 2. a baixa ocorrência de incidência de ondas com ângulos oblíquos com respeito à tendência geral de orientação da linha de costa (menos de 19%) considerando diferentes direções de campos de onda; 3. a elevada eficiência na atenuação da energia das ondas pelos esporões e; 4. a gradação lateral dos sedimentos observada por Oliveira *et al.* (2018).

Contudo, a aparente estabilidade dos arcos praiiais pode estar comprometida dentro de um período de décadas a século, devido ao processo de atenuação das ondas sobre os esporões submersos resultar na sua progressiva erosão, diminuindo a sua eficiência no processo de atenuação de onda e aumentando a quantidade de energia de onda transmitida para a linha de costa dos arcos praiiais, aumentando a sua progressiva mobilidade (Elírio Toldo, comunicação pessoal, Nov 2019).

Ademais, os resultados apresentados demonstraram que não é apropriado estender o comportamento de um esporão para os demais, em decorrência das modificações sofridas pelas ondas devido a fatores condicionantes locais, resultando em alterações, principalmente, na magnitude da deriva litorânea e, por sua vez, na taxa de suprimento de sedimentos para o esporão, fator controlador da sua evolução morfológica.

Por fim, conclui-se que a hipótese apresentada foi confirmada: os esporões encontram-se em uma fase de crescimento limitada devido à redução significativa no suprimento de sedimentos, conforme pôde ser evidenciado (1) pelo comportamento predominantemente estável da linha de costa dos arcos praiiais em escala histórica, com a ausência de taxas de retração costeira na maior escala temporal de análise; observação ratificada pelas (2) reduzidas taxas de aporte sedimentar para os esporões (2.900 m³/ano para o esporão Dona Maria e 900 m³/ano para o esporão do Vitoriano), tendo em vista a magnitude das feições geomorfológicas, e (3) pela canibalização do setor proximal da porção submersa do esporão do Vitoriano, resultado do reduzido aporte de sedimentos e do acentuado retrabalhamento sedimentar induzido pela ação das ondas.

LIMITAÇÕES DA PESQUISA E RECOMENDAÇÕES PARA TRABALHOS FUTUROS

O presente trabalho de Tese analisou a morfodinâmica de esporões arenosos cuspidados na margem de sistemas lagunares em escala de evento à escala histórica com o emprego de distintas abordagens: 1. a análise da mobilidade da linha de costa; 2. a modelagem das ondas geradas por ventos na Lagoa dos Patos; 3. e os resultantes padrões de transporte sedimentar, acompanhado da proposição de um modelo conceitual de balanço regional dos sedimentos. Entretanto, como todo trabalho, apresenta limitações que podem ser contornadas, em geral, com mais dados de campo. Além disso, existe um vasto campo de trabalho para ser realizado. As limitações deste trabalho e recomendações para trabalhos futuros são apresentadas a seguir.

O modelo utilizado foi validado com dados de ondas medidos em campo, e os resultados de transporte corroboram os resultados de estudos anteriores, indicando a boa representação da área de estudo para propósitos científicos. Para tornar o modelo ainda mais robusto, é recomendada a realização de medições de correntes litorâneas e do transporte de sedimentos em campo. Além disso, este trabalho considerou apenas o transporte no tamanho de grão D50, e sugere-se uma detalhada caracterização sedimentológica de toda a região para a investigação do transporte das diferentes frações de grãos que compõem a margem lagunar analisada.

Recomenda-se, também, o estudo da morfodinâmica dos esporões arenosos em menores e maiores escalas temporais e espaciais. Para tanto, sugerem-se o contínuo monitoramento das variações na posição da linha de costa com as imagens LandSat e a aquisição de imagens de satélite ou fotografias áreas de maior resolução espacial, a fim de permitir uma análise mais detalhada das taxas de variação da posição da linha de costa.

Sugere-se, também, um monitoramento com a realização de perfis topográficos para melhor caracterização das praias lagunares e geração de base de dados para análise do transporte transversal de sedimentos. Este pode ser complementado com modelagem, utilizando-se modelos capazes de reproduzir processos como sobrelavagem (por exemplo, XBeach).

O modelo conceitual do balanço regional de sedimentos da região é uma das primeiras aproximações, depois de Toldo (1994), e mais estudos ainda necessitam ser conduzidos a fim de fornecer mais informações e a sua validação. Recomenda-se a quantificação das contribuições das fontes continentais e potenciais impactos oriundos de modificações desses aportes, tendo em vista que atualmente estão sendo realizadas ações que visam à desmobilização de 11 represas e à recomposição da mata ciliar do Arroio Velhaco pelo Comitê de Gerenciamento da Bacia Hidrográfica do Rio Camaquã.

Propõe-se, também, a realização de novas abordagens, como a acoplagem entre o modelo de Evolução da Linha de Costa (“*Coastline Evolution Model*”) (modelagem sintetista, na qual apenas os elementos essenciais que regem um determinado fenômeno são considerados para a representação do comportamento costeiro em larga-escala) e o modelo SWAN (modelagem reducionista, que contabiliza os processos de transformação de ondas em águas rasas), no intento de compreender como os fatores regentes da evolução costeira de feições rítmicas de larga escala em ambiente lagunar se inter-relacionam e atuam nas diferentes escalas.

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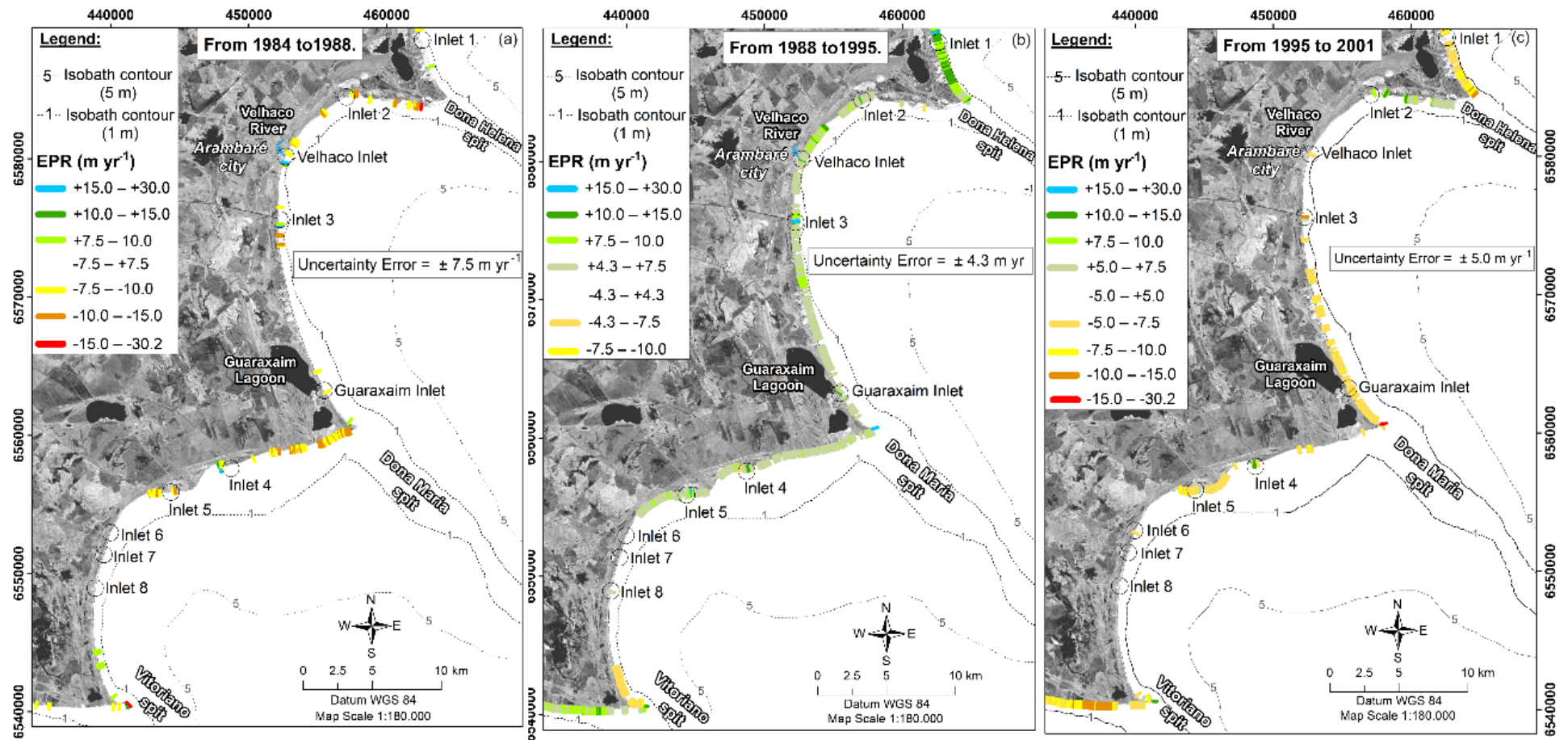
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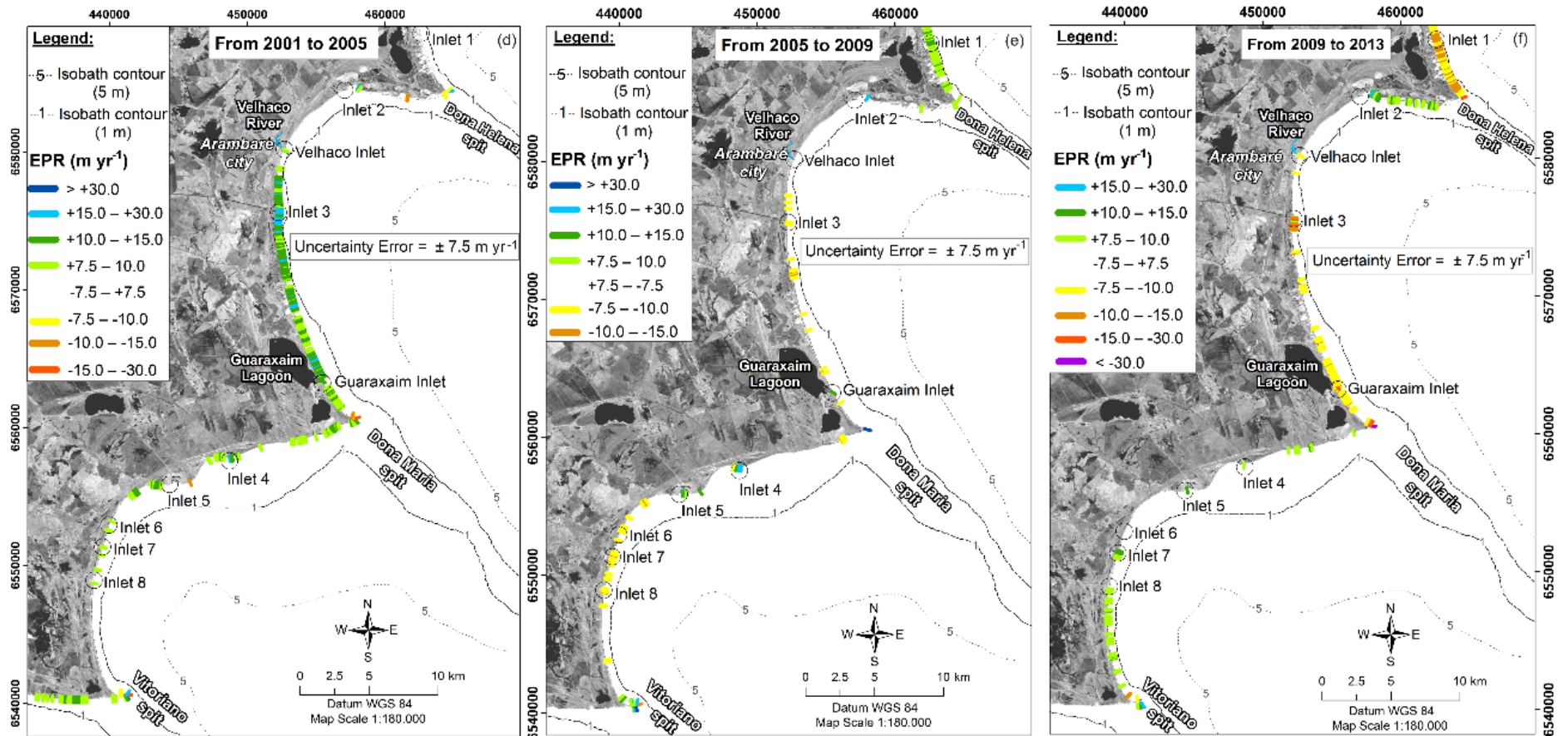
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APÊNDICES

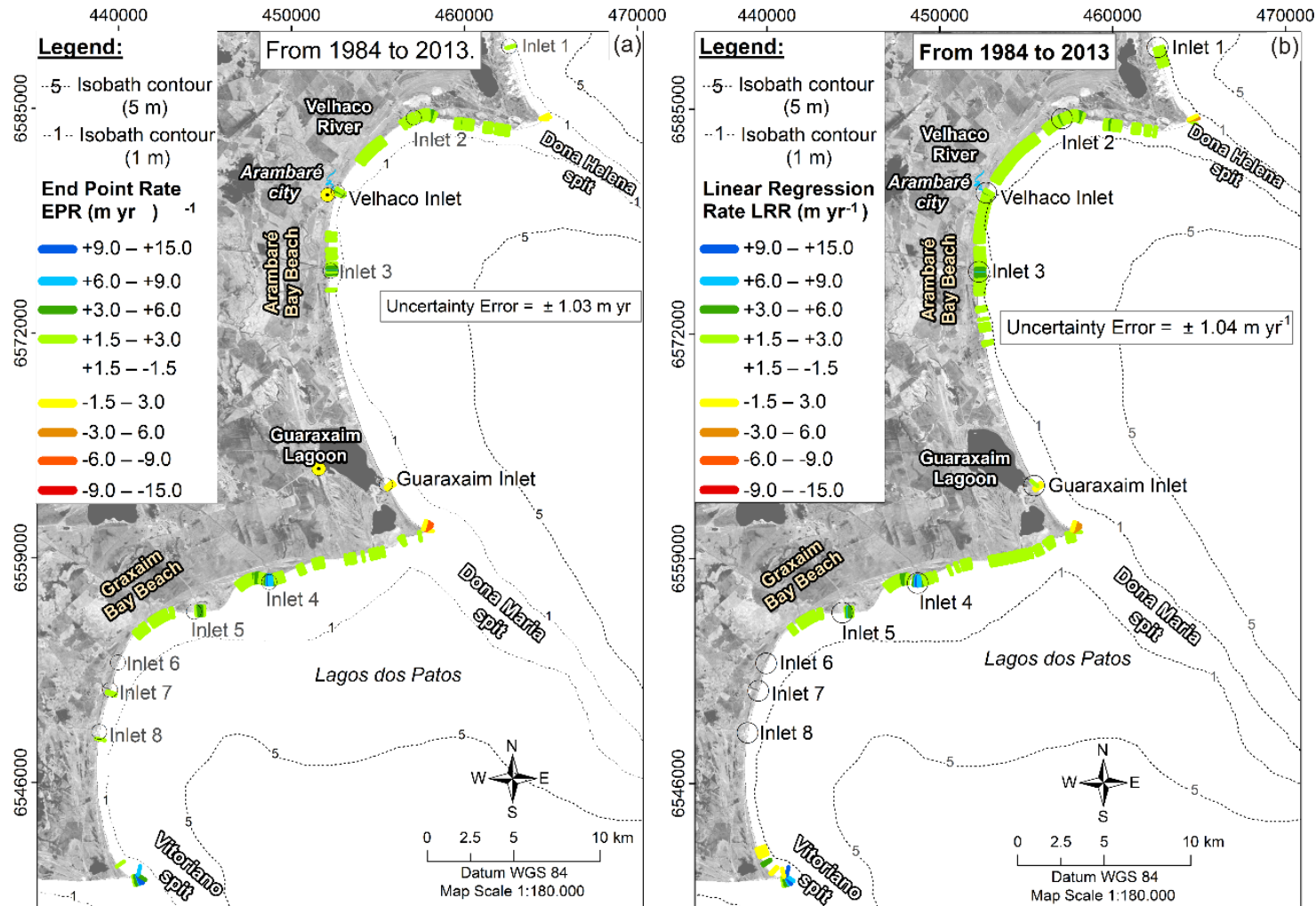
Apêndice A – Variação da posição da linha de costa em períodos interanuais: a) entre os anos de 1984 a 1988, b) 1988 a 1995 e c) 1995 a 2001.



Apêndice B – Variação da posição da linha de costa em períodos interanuais: a) entre os anos de 2001 e 2005, b) 2005 e 2009 e c) 2009 e 2013.



Apêndice C – Mudanças costeiras em escala histórica, entre os anos de 1984 a 2013, considerando as estatísticas (a) End-Point-Rate (EPR) e (b) Linear Regression Rate (LRR).



Apêndice D - Experimental set-ups of the numerical settings used in the sensitivity tests.

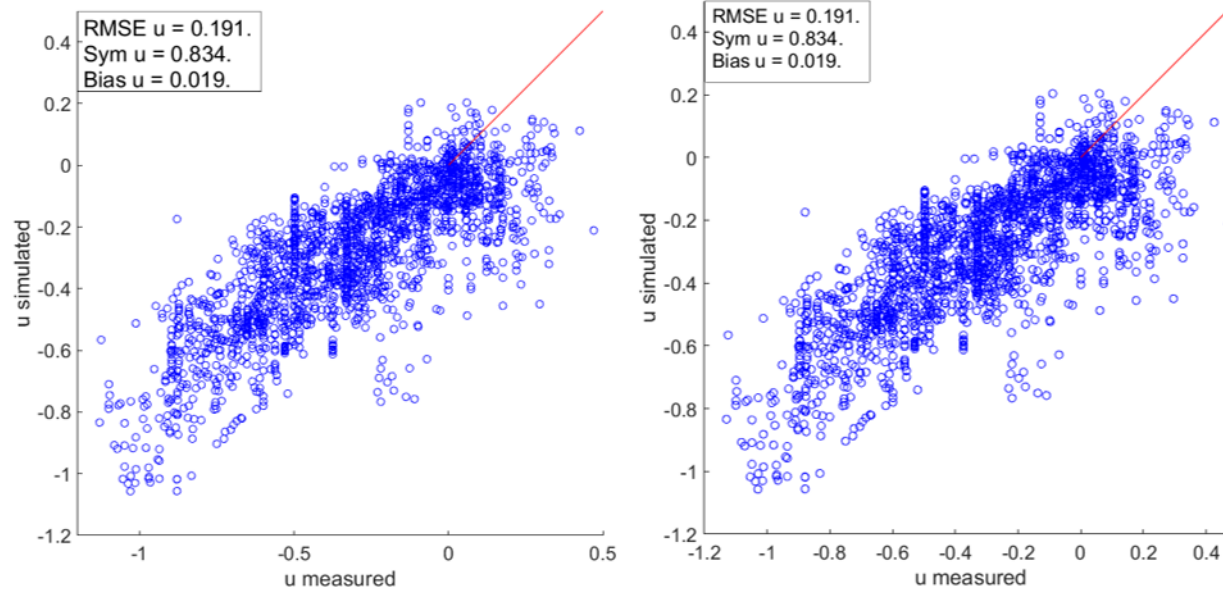
| Set-ups | Numerical Parameters | | | | | | Physical Parameters | | | | | | | |
|---------|----------------------|------------|---------------------|-----------------|----------------|---------------------|---------------------------|-------------------------------|-------------------------|------------------------|-------------------------------|--------------|-------------|------------|
| | Name | Comp. Mode | Coupling Int. (min) | Time Step (min) | Iterations n°. | Dir. Resolution | Freq. Space | Wind Forcing | Bottom Friction | Depth-induced breaking | Non-Linear Triad Interactions | Whitecapping | Diffraction | Refraction |
| Run 1 | Stationary | 360 | - | 15 | 10° | 0.05-1Hz 24 bins | Uniform wind field | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 2 | Stationary | 60 | - | 120 | 10° | 0.05-1Hz 24 bins | Uniform wind field | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 3 | Non-stationary | 360 | 60 | 15 | 10° | 0.05-1Hz 24 bins | Uniform wind field | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 4 | Non-stationary | 360 | 60 | 45 | 10° | 0.05-1Hz 24 bins | Uniform wind field | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 5 | Non-stationary | 180 | 60 | 15 | 10° | 0.05-1Hz 24 bins | Uniform wind field | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 6 | Non-stationary | 60 | 60 | 15 | 10° | 0.05-1Hz 24 bins | Uniform wind field | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 7 | Non-stationary | 60 | 60 | 15 | 5° | 0.05-1Hz 24 bins | Uniform time-varying wind | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 8 | Non-stationary | 60 | 60 | 15 | 5° | 0.05-1Hz 24 bins | Uniform time-varying wind | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Deactivated | Deactivated | Activated | Activated |
| Run 9 | Non-stationary | 60 | 60 | 15 | 5° | 0.05-1Hz 24 bins | Uniform time-varying wind | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Westhuyzen et al. (2007) | Deactivated | Activated | Activated |

| | | | | | | | | | | | | | | |
|--------|----------------------------|-----------|-----------|-----------|-----------|------------------------------|-------------------------------------|---|-------------------------------------|--------------------------------|--|------------------|------------------|------------------|
| Run 10 | Non-stationary | 60 | 60 | 15 | 10° | 0.05-1Hz 24 bins | Uniform time- varyind wind | Jonswap coeff. 0.067 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 11 | Non-stationary | 60 | 60 | 15 | 10° | 0.05-1Hz 24 bins | Uniform time- varyind wind | Madsen et al. Coeff. 0.05 m | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 12 | Non-stationary | 360 | 60 | 15 | 10° | 0.05-1Hz 24 bins | Uniform time- varyind wind | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Deactivated | Komen et al. (1984) | Deactivated | Activated | Activated |
| Run 13 | Non- stationary | 60 | 60 | 45 | 5° | 0.05-1 Hz 24 bins | Uniform wind field | Jonswap coeff. 0.038 m2s-3 | Alpha: 1 Gamma: 0.73 | Alpha:0.1 Beta: 2.2 | Westhu ysen et al. (2007) | Activated | Activated | Activated |

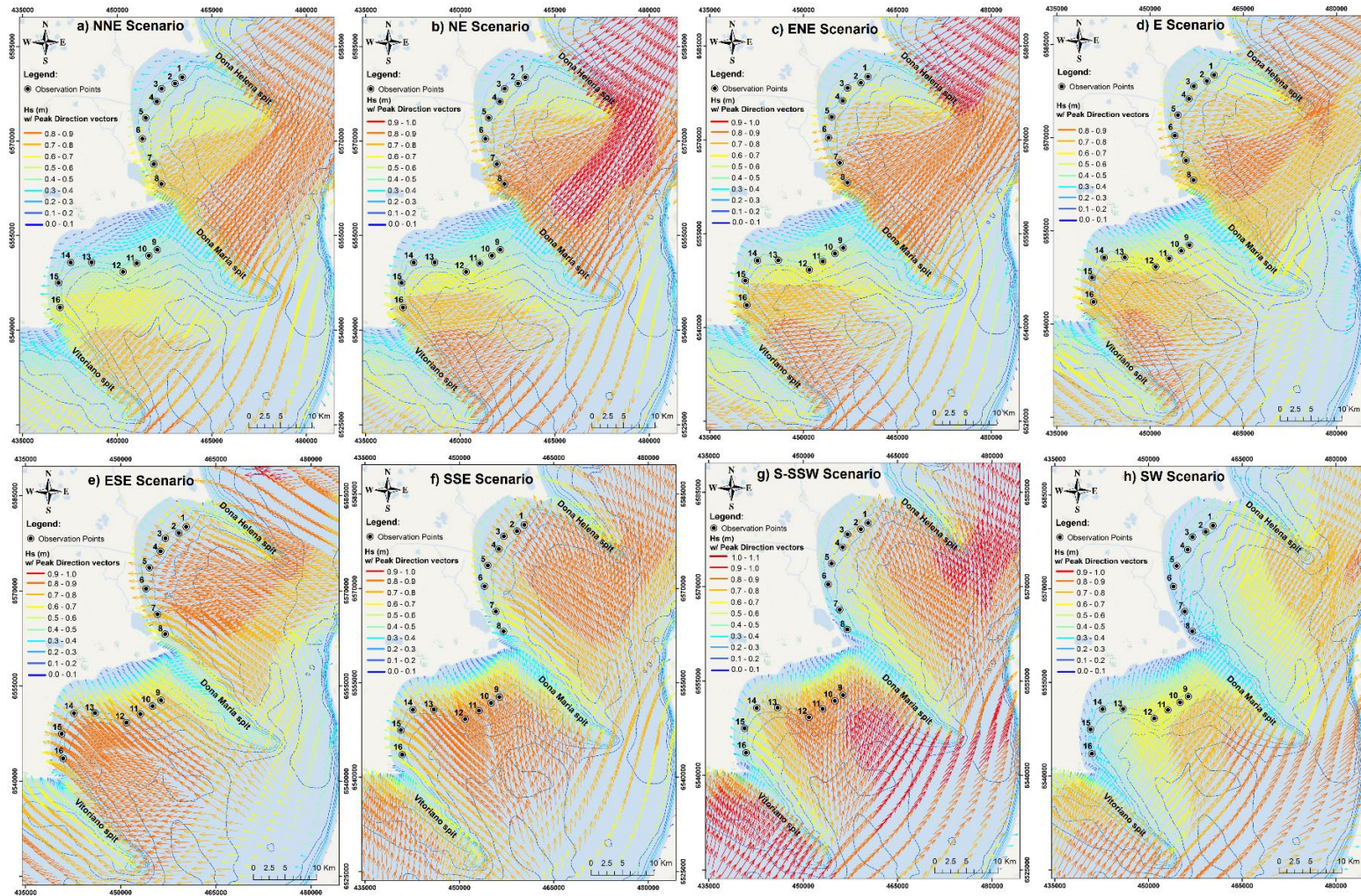
Apêndice E - Statistic results of the sensitivity tests.


| Statistics Name | RMSE | | | | Symmetrical Slope | | | |
|--------------------|---------|---------|-------|--------|-------------------|--------|-------|-------|
| | RMSE Hs | Rmse Tp | RmseU | Rmse V | Sym Hs | Sym Tp | Sym U | Sym V |
| Run 01 n=129 | 0.25 | 0.98 | 0.22 | 0.22 | 0.73 | 0.76 | 0.76 | 0.62 |
| Run 02 n=129 | 0.25 | 1.00 | 0.23 | 0.22 | 0.73 | 0.76 | 0.77 | 0.62 |
| Run 03 n=129 | 0.25 | 0.90 | 0.20 | 0.22 | 0.75 | 0.77 | 0.77 | 0.66 |
| Run 04 n=129 | 0.25 | 0.90 | 0.20 | 0.22 | 0.75 | 0.78 | 0.77 | 0.67 |
| Run 05 n=129 | 0.23 | 0.88 | 0.21 | 0.22 | 0.74 | 0.79 | 0.78 | 0.63 |
| Run 06 n=769 | 0.21 | 0.82 | 0.20 | 0.21 | 0.75 | 0.80 | 0.79 | 0.63 |
| Run 07 n=769 | 0.21 | 0.81 | 0.19 | 0.21 | 0.76 | 0.80 | 0.79 | 0.62 |
| Run 07.2 n=290 | 0.19 | 0.73 | 0.19 | 0.19 | 0.76 | 0.81 | 0.79 | 0.68 |
| Run 08 n=769 | 0.42 | 0.53 | 0.40 | 0.28 | 1.60 | 0.98 | 1.61 | 1.55 |
| Run 09 n=290 | 0.20 | 0.65 | 0.19 | 0.19 | 0.75 | 0.84 | 0.78 | 0.65 |
| Run 10 n=769 | 0.22 | 0.87 | 0.20 | 0.20 | 0.79 | 0.75 | 0.75 | 0.62 |
| Run 11 n=769 | 0.23 | 0.91 | 0.22 | 0.20 | 0.69 | 0.76 | 0.71 | 0.62 |
| Run 12 n=129 | 0.25 | 0.90 | 0.20 | 0.22 | 0.75 | 0.78 | 0.77 | 0.66 |

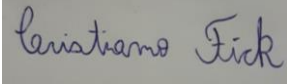
Apêndice F - Comparison between the U and V components converted from the magnitude and direction of the modelled and measured wave data, from February to April, 2015.



Apêndice G - Magnitude of significant wave height with wave peak Direction vectors for the a) NNE, b) NE, c) ENE, d) E, e) ESE, f) SSE, g) S-SW, h) SW scenarios.




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| sANEXO I | |
| Título da Dissertação/Tese: | |
| “Morfodinâmica de Esporões Arenosos Lagunares Cuspidados, Lagoa dos Patos, Brasil” | |
| Área de Concentração: Geologia Marinha | |
| Autora: Inaiê Malheiros Miranda | |
| Orientador: Prof. Dr. Elirio Ernestino Toldo Junior | |
| Examinadora: Profa. Dra. Susana Costas | |
| Data: 06/08/2020 | |
| Conceito: A | |
| PARECER: | |
| <p>O trabalho apresentado pela candidata Inaiê merece o reconhecimento aqui demonstrado pelo conceito apos ter demonstrado que posue a madurez científica que o grado requiere. Esta ficou bem demonstrada pelo trabalho de disertação apresentado, o qual apresenta uma estruturado muito coerente de encontro a hipotese proposta e questoes cientificas identificas e respondidas em este trabalho. As questoes cientificas identificadas são importantes do ponto de vista local, e não so, pois tambem ajudaram para contribuir para o conhecimento geral do funcionamento dos esporoes lagunares.</p> | |
|  | |
| Assinatura: | Data: 6 de Junho de 2020 |
| Ciente do Orientador: | |
| Ciente do Aluno: | |

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|---|---|
| ANEXO I | |
| Título da Dissertação/Tese: | |
| “Morfodinâmica de Esporões Arenosos Lagunares Cuspidados, Lagoa dos Patos, Brasil” | |
| Área de Concentração: Geologia Marinha | |
| Autora: Inaiê Malheiros Miranda | |
| Orientador: Prof. Dr. Elirio Ernestino Toldo Junior | |
| Examinador: Dr. Cristiano Fick | |
| Data: 08/06/2020 | |
| Conceito: A | |
| PARECER: | |
| <p>A tese de doutorado apresentada pela doutoranda Inaiê Malheiros Miranda constitui um documento muito bem estruturado, dentro da norma do PPGGEO. Com objetivos claros e bem definidos, perguntas científicas pertinentes ao tema proposto e premissas e hipóteses igualmente satisfatórias, o trabalho é introduzido de maneira convincente. A revisão bibliográfica supre o embasamento teórico abordado na sequência do estudo dos esporões arenosos cuspidados da porção central da Lagoa dos Patos. As metodologias empregadas, expostas ao longo dos artigos, expressam o alto grau de rigor adotado, tanto na análise temporal da linha de costa (imagens de satélite - LANDSAT) quanto na hidrodinâmica das ondas e seu papel no transporte de sedimentos (modelagem numérica – SWAN e DELFT 3D). Os resultados, descritos detalhadamente, trazem avanço no entendimento da evolução dos esporões, que devido ao baixo suprimento de sedimentos da região, a importante atenuação da energia das ondas e a bi direcionalidade da deriva litorânea (comandada pelas diferentes intensidades e direções de vento), encontram-se em estágio de equilíbrio dinâmico, dentro de uma escala de tempo decadal. A qualidade dos artigos científicos é plenamente satisfatória, sendo que dois deles já estão publicados em periódicos de grande visibilidade internacional. O capítulo integrador consegue de modo eficiente unir as diferentes abordagens dos artigos aos objetivos e perguntas científicas propostas. No entanto, a ausência de discussões mais críticas quanto aos métodos utilizados e da proposição de um modelo generalista (ou refinamento de modelos existentes: Zenkovich, 1959) da evolução de esporões arenoso em sistemas lagunares constituem pontos que poderiam ter sido melhor explorados na tese. As figuras apresentadas são satisfatórias, sendo que algumas carecem de elementos que facilitem o entendimento do leitor. Concluindo, a presente tese de doutorado traz de fato elementos inovadores e inéditos no estudo dos esporões arenosos cuspidados da porção central (margem oeste) da Lagoa dos Patos, atingindo os objetivos e confirmando sua hipótese.</p> | |
| Assinatura: |  Data: 08/06/2020 |

Ciente do Orientador:

Ciente do Aluno:

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| ANEXO I |
| Título da Dissertação/Tese: |
| “Morfodinâmica de Esporões Arenosos Lagunares Cuspidados, Lagoa dos Patos, Brasil” |
| Área de Concentração: Geologia Marinha |
| Autora: Inaiê Malheiros Miranda |
| Orientador: Prof. Dr. Elirio Ernestino Toldo Junior |
| Examinador: Prof. Dr. Lauro Julio Calliari |
| Data: 8 de junho de 2020 |
| Conceito: A |
| PARECER: |
| <p>A tese aborda aspectos inéditos sobre a morfodinâmica de esporões arenosos em Lagoas Costeiras. Os novos dados de levantamentos evolutivos da linha de costa a curto e médio prazo, a importância dos mesmos na modificação das ondas e por fim o balanço sedimentar ao longo dos mesmos fornecem indicações sobre tendências de evolução futura dessas feições importantes na margem lagunar. A tese está bem estruturada com introdução, hipótese, objetivos e metodologia bem definidos. Os objetivos foram alcançados. Nota-se ao longo da tese uma extensa lista de referências bibliográficas ligadas a essas feições. A situação atual de dois trabalhos publicados e um terceiro já aprovado incorporados a tese consubstanciam a sua qualidade. A tese preenche completamente os requisitos para o doutorado.</p> <p>Estas são nossas considerações</p> |
|  |
| Assinatura: |
| Data: 08 de junho de 2020 |
| Ciente do Orientador: |
| Ciente do Aluno: |