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

PROCESSOS SEDIMENTARES NO CANAL DE ACESSO AO ESTUÁRIO DA LAGOA DOS PATOS, BRASIL

MARINE JUSIANE BASTOS DA SILVA

ORIENTADOR – Prof. Dr. Iran Carlos Stalliviere Corrêa
COORIENTADOR – Prof. Dr. José Antônio Scotti Fontoura

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BANCA EXAMINADORA

Prof. Dr. José Gustavo Natorf de Abreu – Universidade do Vale do Itajaí (UNIVALI)

Prof. Dr. Miguel da Guia Albuquerque – Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Sul (IFRS)

Prof. Dr. Jair Weschenfelder – Instituto de Geociências, Universidade Federal do Rio Grande do Sul (UFRGS)

Tese de Doutorado apresentada como requisito parcial para a obtenção do Doutor em Ciências.

Porto Alegre, 2023

CIP - Catalogação na Publicação

Silva, Marine Jusiane Bastos da
PROCESSOS SEDIMENTARES NO CANAL DE ACESSO AO ESTUÁRIO DA LAGOA DOS PATOS, BRASIL / Marine Jusiane Bastos da Silva. -- 2023.
142 f.
Orientador: Iran Carlos Stalliviere Corrêa.

Coorientador: Jose Antonio Scotti Fontoura.

Tese (Doutorado) -- Universidade Federal do Rio Grande do Sul, Instituto de Geociências, Programa de Pós-Graduação em Geociências, Porto Alegre, BR-RS, 2023.

1. Sedimentação. 2. Lagoa dos Patos. 3. Porto do Rio Grande. 4. Descarga. 5. Assoreamento. I. Corrêa, Iran Carlos Stalliviere, orient. II. Fontoura, Jose Antonio Scotti, coorient. III. Título.

Elaborada pelo Sistema de Geração Automática de Ficha Catalográfica da UFRGS com os dados fornecidos pelo(a) autor(a).

"Sem as longas horas da contemplação,
o que vemos é só o que vemos".

Pe. Fábio de Melo

Dedico esta tese à minha mãe,
Ivani Berchete Bastos, meu maior
exemplo de dedicação e força.

.

AGRADECIMENTOS

Sou grata a Deus por todas as bênçãos que Ele me concedeu, pelo Seu constante amparo e por ser a minha fonte de força. Agradeço a Ele por todas as pessoas que compartilharam esse caminho comigo, que me inspiraram e que possibilitaram a realização desse sonho.

Agradeço à minha mãe, Ivani Berchete Bastos, por tudo o que fez para que esse dia chegasse: pelo tempo que dedicou, por sua atenção e por ter, desde cedo, me mostrado o quanto a educação era importante. Foi minha mãe que me ensinou a ler, a calcular, a estudar – com toda sua paciência e todo seu amor. Isso fez toda a diferença na minha vida. Obrigada por ter sido minha incansável companheira, por dividido comigo os bons momentos e os mais angustiantes (que foram muitos). Nada disso teria existido sem ti. Essa conquista é nossa.

Ao meu pai Jones Silva (*in memoriam*), agradeço por seu amor e por sempre ter confiado tanto em mim. Aos meus avós, Leonilda Bastos (*in memoriam*) e Orlando Bastos (*in memoriam*), agradeço por terem me dado o que há de mais precioso: o seu tempo e sua atenção. Ao meu tio, José Nazareno Bastos (*in memoriam*), agradeço por toda sua torcida e por ser meu companheiro em quase todo esse percurso. Eles me ensinaram as mais valiosas lições sobre amor e perseverança. Eles foram minha maior bênção e são a minha maior saudade. Sem eles nada teria sido possível.

Ao professor Iran Corrêa, agradeço imensamente por ter me aceito como sua orientanda, por ter depositado confiança neste trabalho e em mim. Agradeço pela sua pronta disponibilidade sempre que solicitava alguma demanda ou sempre que necessitava de sua orientação (que geralmente envolviam longos – muito longos – e-mails). Muito obrigada por tudo.

Ao professor José Fontoura, meu sincero agradecimento por todas as portas que abriu para mim ao longo de mais de dez anos. Obrigada por ter sido sempre uma referência nas decisões que envolviam a vida acadêmica. Obrigada pelas longas discussões (muito longas) sobre os resultados, sempre com senso crítico e atenção plena. Agradeço pelos seus conselhos, pela confiança depositada em mim e, sobretudo, pelo tempo que dedicou para que esse trabalho se tornasse realidade.

Ao professor Miguel Albuquerque, agradeço por ter me apresentado, ainda no ensino médio, o mundo acadêmico e a ciência. Grande parte dessa conquista se deu devido a essas oportunidades. Muito obrigada por sua humildade e por ser esse grande incentivador de sonhos e de crescimento.

Ao professor Christian Serpa, agradeço por sua grande parceria ao longo desse caminho na academia e, principalmente, no desenvolvimento deste estudo. Sua colaboração foi imprescindível para o desenvolvimento da metodologia empregada. Obrigada por sua disponibilidade, atenção e paciência.

Ao professor Lauro Calliari (*in memoriam*), agradeço por ter sido um importante incentivador desta pesquisa. Agradeço pelas inúmeras portas que abriu para ciência, sendo uma eterna inspiração para aqueles que tiveram a oportunidade de presenciar seu entusiasmo e sua paixão pelas ciências do mar.

Ao professor Leo Hartmann, agradeço imensamente por suas aulas e por sua humildade para ensinar. Obrigada por ter se disposto inúmeras vezes a ler manuscritos de artigos, analisar a apresentação de figuras e tabelas, sempre de forma tão responsável e atenciosa. Obrigada por sua paciência e comprometimento. Eu não teria conseguido sem o seu auxílio.

Ao time de professores do LEC/LIFE da FURG: Ana Paula Gomes, Débora Machado, Marco Romeu, Natália Lemke, Rodrigo Davesaak, Waldir Pinto, agradeço, primeiramente, por tudo que me ensinaram como professores e, também, por me acolherem em muitos momentos ao longo dos últimos anos. Agradeço aos melhores técnicos de laboratório e, também, grandes parceiros e incentivadores desse sonho: Veridiana Herreira (minha grande e querida amiga) e Marcelo Goulart. Muito obrigada por tudo que fizeram para que esse trabalho se tornasse realidade, pelo carinho com que tratam os alunos, sempre dispostos a fazer o que era preciso (e até mais). Vocês fazem e fizeram toda diferença.

Estendo meus agradecimentos aos queridos amigos que a vida me presenteou nessa caminhada acadêmica: Gilberto Rech, Luiza Fiorini, Laís Pool, Carolina De-Zotti, Kaue Domingues. Vocês tornaram a vida acadêmica muito mais leve e divertida. Ao Gilberto, em especial, agradeço pelo tanto que me ajudou “emprestando seus ouvidos” para eu contar as descobertas da tese 1.000x (no mínimo) nesse último ano.

Às minhas amigas e fiéis companheiras, na boa e na ruim (mais ainda): Ana Tubino e Tainã Peres, obrigada pela força que sempre me dão, em todos os momentos. Vocês são um grande presente. Às minhas grandes amigas Camila Raubach e Karine Leal, agradeço imensamente pelo carinho, pelo incentivo e pelas palavras sempre gentis. Aos meus amigos, Ricardo Esteves e Elizângela Pintado, sou imensamente grata por terem estado comigo nos momentos que mais precisei, ao longo desta caminhada. Estendo meus agradecimentos às minhas tias de coração Oldeci Larroque, Vera Silveira e Maria Neli Oliveira, sempre tão companheiras e carinhosas. Ao meu irmão, Juliano Silva, agradeço por seu carinho e incentivo. Tenho MUITA sorte de poder contar com todos vocês!

Agradeço aos professores Elaine Goulart e Osmar Möller (FURG), que prontamente tiraram dúvidas sobre dados utilizados nesta tese.

Agradeço aos professores que gentilmente aceitaram o convite para compor a banca examinadora.

Agradeço, em especial, às instituições IFRS (Câmpus Rio Grande), FURG e UFRGS, onde estudei. Nós, alunos, somos “construídos a muitas mãos”, com muito esforço e generosidade dos profissionais que nelas atuam (técnicos e professores). Àqueles que cruzaram meu caminho nessas instituições, muito obrigada.

Agradeço aos meus colegas do Programa de Pós-Graduação em Geociências com quem, ao longo de quatro anos, dividi bons momentos e preocupações da vida acadêmica. Estendo meus agradecimentos aos colegas do curso de Direito da FURG pelo auxílio que me deram sempre que foi necessário.

Essa pesquisa só foi possível devido ao fornecimento de dados pela empresa pública Portos RS. Sem esses dados, a pesquisa não teria sido realizada. Agradeço, especialmente, ao Mario Dutra e ao Sávio Novo (servidores da Portos RS), por tudo o fizeram para que esse trabalho fosse possível, por terem sido incansáveis sanando dúvidas e sempre muito atenciosos. Sem o incentivo dessa instituição e desses profissionais, essa tese não teria sido desenvolvida. Mil vezes obrigada!

Agradeço à UFRGS, à FURG e ao CNPq, instituições que possibilitaram o desenvolvimento desta tese.

A verdade é que, na ciência e na vida, não conseguimos avançar sozinhos. Eu tenho muita sorte por ter contado com vocês nessa caminhada. De coração, os meus mais sinceros agradecimentos.

RESUMO

A evolução morfológica do fundo dos canais de navegação é resultado da interação de vários mecanismos que afetam a dinâmica dos sedimentos. Em cada ambiente, existem condições específicas que influenciam a configuração do fundo. Nos canais de navegação, a deposição de sedimentos é um aspecto crucial, e a identificação de padrões de sedimentação é essencial para o desenvolvimento de estratégias sustentáveis de manutenção de portos e hidrovias. No sul do Brasil, um único canal conecta o Oceano Atlântico à Lagoa dos Patos, sendo, também, o acesso marítimo ao Porto do Rio Grande. A deposição de sedimentos nesse canal resulta na necessidade de realização de dragagens periódicas. Esta tese tem como objetivo investigar a evolução do fundo do canal de acesso ao estuário da Lagoa dos Patos. Foram utilizados dados de levantamentos batimétricos realizados entre os anos de 2001 e 2020 pela Autoridade Portuária, juntamente com dados de vazão na desembocadura do estuário. A metodologia foi baseada na elaboração de modelos digitais de elevação, a partir dos quais foram calculadas taxas líquidas de sedimentação e gerados mapas de evolução do fundo. Esses dados foram avaliados conjuntamente com dados de vazão, visando identificar uma possível relação entre a dinâmica de sedimentos no fundo e o comportamento hidrológico observado na região. A análise dos dados revelou informações inéditas sobre características do fundo e padrões de sedimentação. Os resultados indicaram uma variação significativa nas taxas líquidas de sedimentação. Dentre as regiões analisadas, foram identificadas áreas propensas à deposição de sedimentos, sendo elas: (i) a porção noroeste da bacia do Porto Novo; (ii) a margem oeste do canal de acesso ao Porto Novo, adjacente à Coroa do Boi; (iii) a margem leste do canal interno, adjacente à Coroa Dona Mariana; (iv) a porção do canal localizada no domínio marinho na configuração anterior a 2009; (v) a região entre os molhes da Barra. A descarga do estuário mostrou-se como um fator importante no controle da deposição de sedimentos na porção abrigada do canal, uma vez que menores taxas líquidas de sedimentação foram associadas a períodos de fluxo de vazante mais intensos. No entanto, essa relação parece estar limitada à porção abrigada do canal, já que esse comportamento não foi observado quando analisados dados da porção do canal situada em domínio marinho. Os resultados obtidos por meio da metodologia empregada destacam, sobretudo, a importância do monitoramento do ambiente para caracterizar efetivamente seu comportamento.

Palavras chave: Sedimentação; Lagoa dos Patos, Porto do Rio Grande, descarga, assoreamento.

ABSTRACT

The morphological evolution of navigation channels is the result of the interaction between multiple mechanisms that affect sediment dynamics. In each environment, specific mechanisms play a role and influence the configuration of the bottom. In navigation channels, sediment deposition is a crucial aspect, and the identification of sedimentation patterns is essential for the development of sustainable strategies for maintaining ports and waterways. In southern Brazil, a single channel links the Atlantic Ocean to the Patos Lagoon, also serving as the unique maritime access to Port of Rio Grande. Periodic dredging is required in this channel due to sediment deposition. This thesis aims to investigate the evolution of the access channel to the Patos Lagoon estuary. Bathymetric survey data conducted between 2001 and 2020 by the Port Authority and discharge data at the estuary's mouth were used. The methodology was based on the creation of digital elevation models, which were used to calculate net sedimentation rates and generate bed evolution maps. These data were evaluated in conjunction with discharge data to identify possible relations between sediment dynamics in the bottom and the hydrological data of the inlet’s mouth. The data analysis revealed unprecedented information about bottom characteristics and sedimentation patterns. The results indicated a significant variation in net sedimentation rates. Among the analyzed regions, areas prone to sediment deposition were identified, including: (i) the northwestern portion of the Porto Novo basin; (ii) the western margin of the access channel to Porto Novo, adjacent to Coroa do Boi; (iii) the eastern margin of the internal channel, adjacent to Coroa Dona Mariana; (iv) the portion of the channel located in the marine domain in the configuration prior to 2009; (v) the region between the jetties. Discharge was an important factor in controlling sediment deposition in the internal portion of the channel, as lower net sedimentation rates were associated with periods of more intense ebb flow. However, this relation appears to be limited to the internal portion of the channel, as this behavior was not observed when analyzing data from the portion of the channel located in the marine domain. The results highlight, above all, the importance of environmental monitoring in effectively characterizing its behavior.

Key words: sedimentation; Patos Lagoon, Port of Rio Grande, dischage, siltation.

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SUMÁRIO

ESTRUTURA DA TESE

Esta tese de doutorado está estruturada em três (3) artigos submetidos/publicados em periódicos classificados nos estratos Qualis-CAPES A2 e A3. A sua organização compreende as seguintes partes principais:

Capítulo 1 Considerações iniciais. Apresenta os seguintes tópicos: introdução, motivação, hipóteses, descrição da área de estudo, estado da arte, materiais e métodos, delimitação espacial e temporal de cada artigo.

Capítulo 2 Apresenta o artigo científico intitulado "SEDIMENTATION PROCESSES IN THE NAVIGATION CHANNEL OF PATOS LAGOON ESTUARY, SOUTHERN BRAZIL", aceito para publicação no periódico Regional Studies in Marine Science.

Capítulo 3 Apresenta o artigo científico intitulado "SEDIMENT PATTERNS IN THE NAVIGATION CHANNEL OF THE PATOS LAGOON ESTUARY, BRAZIL, BETWEEN 2005 AND 2009", submetido para o periódico Continental Shelf Research.

Capítulo 4 Apresenta o artigo científico intitulado "SILTATION IN THE NAVIGATION CHANNEL OF PATOS LAGOON ESTUARY, BRAZIL, CONSIDERING THE CURRENT CONFIGURATION OF THE JETTIES AND THE CHANNEL", submetido para o periódico Geo-Marine Letters.

Capítulo 5 Considerações finais. Apresenta os seguintes tópicos: síntese, recomendações para trabalhos futuros e referências bibliográficas do capítulo 1.

ANEXOS Incluem os comprovantes de aceite/submissão dos artigos.

CAPÍTULO 1

CONSIDERAÇÕES INICIAIS

1. CONSIDERAÇÕES INICIAIS

1.1 Introdução

Os estuários são ambientes dinâmicos localizados na zona de transição entre o continente e o oceano. Essas áreas costeiras possuem um grande valor ambiental, econômico, social e cultural, por constituírem importantes vias de acesso ao interior do continente e por serem áreas de grande biodiversidade e alta produtividade biológica.

Devido às condições naturais de abrigo, muitos portos são localizados em áreas estuarinas. No sul do Brasil, por exemplo, há importantes portos que estão situados em estuários, como o Porto do Rio Grande, localizado no estuário da Lagoa dos Patos (Rio Grande do Sul); o Porto de Itajaí, no estuário do rio Itajaí (Santa Catarina); e os Portos de Antonina e Paranaguá, no Complexo Estuarino de Paranaguá (Paraná).

Em ambientes estuarinos, a dinâmica de sedimentos, principalmente a deposição de sedimentos, é um dos aspectos mais importantes relacionados a portos. A deposição de sedimentos em canais acarreta a redução de profundidades e consequente limitação do calado das vias navegáveis, podendo representar uma ameaça à segurança da navegação. Dragagens de manutenção constituem a principal estratégia utilizada para o desassoreamento de canais portuários, envolvendo, muitas vezes, altos custos e impactos negativos ao meio ambiente.

O estudo dos processos sedimentares em ambientes estuarinos, especialmente em canais portuários localizados nessas áreas, é fundamental para apoiar a busca por estratégias que visem aprimorar o gerenciamento dos problemas relacionados ao assoreamento. Além disso, tais estudos podem contribuir para o desenvolvimento de alternativas mais sustentáveis, com o objetivo de reduzir custos e impactos ambientais associados a esses processos.

No cenário mundial, filosofias como a *Working with Nature* (Trabalhando com a Natureza), incentivada pela Associação Mundial de Infraestrutura de Transporte Aquaviário (*World Association for Waterborne Transport Infrastructure,* PIANC na sigla em inglês), vêm ganhando destaque. A filosofia expõe que se deve buscar explorar soluções de engenharia que respeitem a natureza. Assim, a ordem para implementação de um projeto consiste em estabelecer a necessidade e os objetivos do projeto, entender o ambiente, identificar oportunidades *win-win* (ganha-ganha) e preparar propostas iniciais que beneficiem a natureza e a navegação. À luz desse conceito, busca-se soluções de engenharia sustentáveis e economicamente viáveis, que reduzam o impacto ambiental das atividades humanas e promovam a conservação e a recuperação dos ecossistemas costeiros.

Na Lagoa dos Patos, o canal de acesso ao estuário é, também, o canal de acesso ao Porto do Rio Grande, cuja infraestrutura portuária está majoritariamente localizada na margem oeste da desembocadura. O Porto do Rio Grande é um dos mais importantes portos no cenário logístico nacional, tendo movimentado mais de 45 milhões de toneladas em 2021 e mais de 37 milhões de toneladas em 2022 (PORTOS RS, 2023). Além disso, com a implementação prevista da Hidrovia da Lagoa Mirim – Lagoa de Patos, o canal constituirá uma importante hidrovia para escoamento da produção de outras regiões.

O canal de acesso experimenta um processo de assoreamento recorrente e dragagens de manutenção são realizadas para garantir o acesso à infraestrutura portuária e a segurança da navegação. Recentemente, grandes investimentos foram realizados visando o aprofundamento do canal de acesso e a extensão dos molhes que fixam a desembocadura.

Esta tese visa ampliar o conhecimento acerca dos processos sedimentares neste canal de acesso ao estuário da Lagoa dos Patos, investigando variações temporais e espaciais na sua morfologia. Embora o entendimento da dinâmica de sedimentos seja fundamental para uma gestão otimizada, ainda são escassos os estudos sobre a dinâmica de sedimentos desse canal.

Estudos voltados para essa temática contribuem tanto em aspectos ambientais quanto em aspectos socioeconômicos, dada a importância ambiental de estuários e a relevância dos portos para economia nacional. Além disso, somente o conhecimento pormenorizado da dinâmica do ambiente é capaz de apoiar a busca por desenvolvimento sustentável.

1.1.1 Motivação

A motivação para o desenvolvimento deste estudo no canal de acesso ao estuário da Lagoa dos Patos se deu em virtude dos seguintes aspectos:

- A carência de estudos relacionados à dinâmica de sedimentos e aos processos de assoreamento no geral e, ainda, a ausência de estudos que considerem a análise de dados *in situ* como levantamentos batimétricos;

- A disponibilização de levantamentos batimétricos do período de 2000 a 2020 pela Autoridade Portuária – Portos RS, compondo uma série de dados que não havia sido analisada em estudos pretéritos;

- As características peculiares do estuário, que possui um regime hidrodinâmico controlado pela combinação da ação do vento e da descarga fluvial (HARTMANN; SCHETTINI, 1991; MÖLLER; CASTAING, 1999; MÖLLER *et al.*, 2001; MÖLLER *et al.*, 2009; MÖLLER; FERNANDES, 2010) e que tem sua desembocadura fixada por dois molhes construídos nas primeiras décadas do século XX (modificados no final dos anos 2000), constituindo uma das maiores obras de engenharia costeira do mundo (CUNHA; CALLIARI, 2009);

- A relevância do Porto do Rio Grande no cenário nacional, evidenciada pela movimentação anual média de 35,7 milhões de toneladas no período entre 2009 e 2022 (PORTOS RS, 2023);

- A importância da análise de dados pretéritos para conhecer o ambiente e compreender seu comportamento, servindo, essa investigação, como mais um instrumento de apoio ao aprimoramento de futuras pesquisas científicas e à gestão portuária e ambiental.

1.1.2 Hipóteses

São hipóteses desse estudo:

(a) Levantamentos batimétricos são uma forma precisa de determinação das caraterísticas morfológicas do canal;

(b) A evolução do fundo varia no tempo e no espaço e há regiões onde há maior tendência à deposição de sedimentos, promovendo o assoreamento local do canal;

(c) As taxas líquidas de sedimentação no canal de acesso são inversamente relacionadas aos níveis de vazão no estuário da Lagoa dos Patos.

1.2 Objetivos

1.2.1 Objetivo geral

Investigar a evolução do fundo do canal de acesso ao estuário da Lagoa dos Patos ao longo do tempo e do espaço, utilizando dados do período entre os anos de 2001 e 2020.

1.2.2 Objetivos específicos

- Identificar as caracterísficas morfológicas do canal;
- Estimar as taxas líquidas de sedimentação para cada periodo e setor analisado;
- Mapear a evolução do fundo para cada período e setor analisado;
- Identificar as principais regiões onde há tendência à deposição ou erosão de sedimentos ou, ainda, à estabilidade das profundidades;
- Correlacionar as taxas líquidas de sedimentação e o mapeamento da evolução do fundo com dados de vazão da desembocadura do estuário;
- Investigar se há padrões sazonais de deposição ou erosão de sedimentos no canal.

1.3 Área de Estudo

A área de estudo desta tese compreende o canal de acesso ao estuário da Lagoa dos Patos que é, também, o canal de acesso ao Porto do Rio Grande. Sendo assim, esta seção tem como objetivo apresentar as principais características da região de estudo e está subdividida em duas subseções: a primeira (1.3.1) delimita as principais características da Lagoa dos Patos, como aspectos da hidrodinâmica, da circulação estuarina e da distribuição de sedimentos, enquanto a segunda (1.3.2) busca apresentar as principais características do canal de acesso e das modificações antrópicas feitas no ambiente.

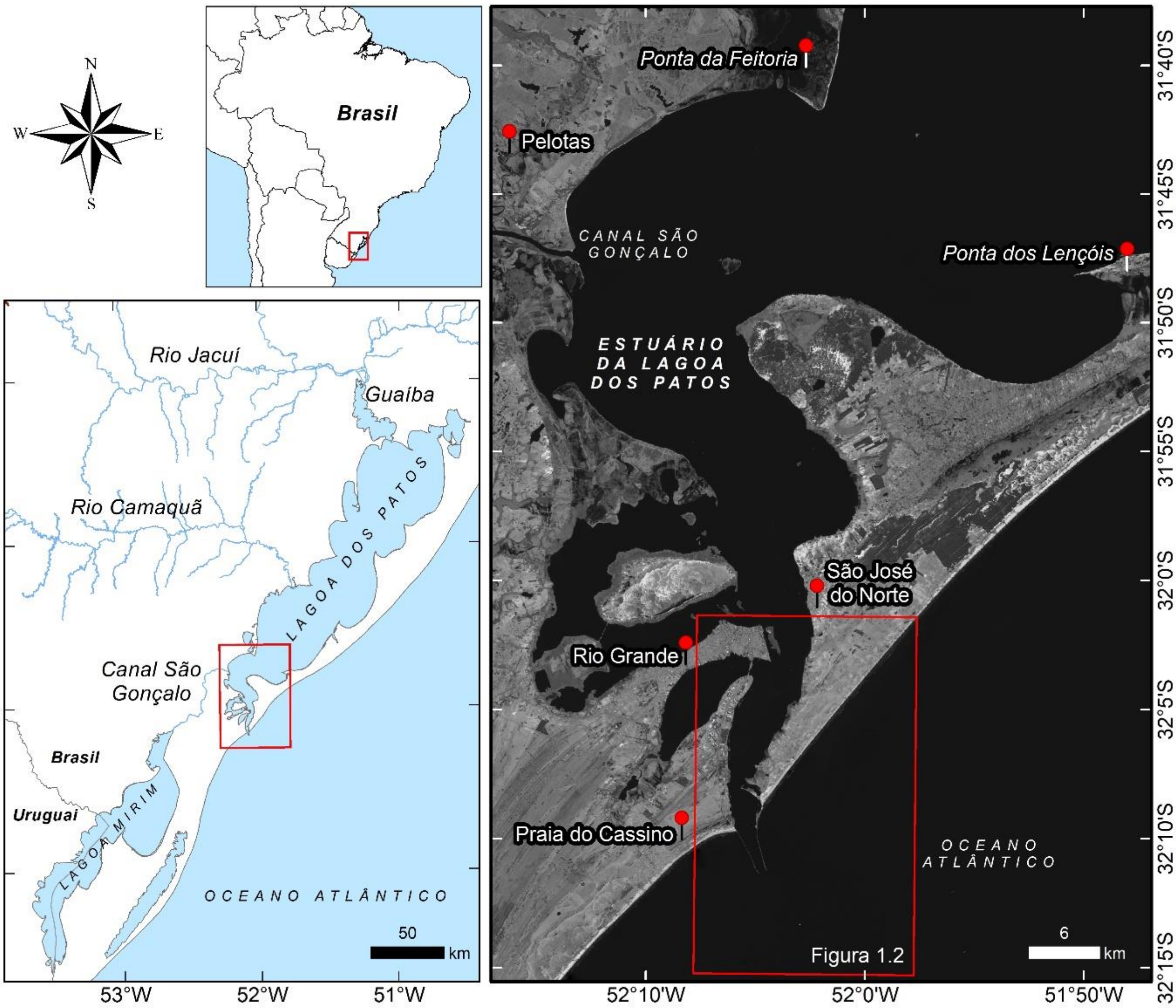
1.3.1 Lagoa dos Patos

A Lagoa dos Patos está localizada no sul do Brasil, no estado do Rio Grande do Sul, e se conecta com a Lagoa Mirim por meio do canal São Gonçalo, totalizando uma bacia de drenagem de 199.000 km² (HARTMANN; SCHETTINI, 1991). O eixo principal da Lagoa tem orientação NE-SO (CALLIARI *et al.*, 2008) (Figura 1.1).

Na região estuarina, situada na porção sul da laguna, um único canal, objeto de estudo desta tese, conecta a Lagoa dos Patos ao Oceano Atlântico (Figura 1.2). O estuário se estende da Barra do Rio Grande até a linha que liga a Ponta dos Lençóis à Ponta da Feitoria (CALLIARI, 1980). Esse limite pode ser deslocado para norte, durante períodos de baixa vazão ou sob ação do vento sul, ou para sul, quando há grande descarga fluvial ou ventos do quadrante norte (CALLIARI *et al.*, 2008).

O estuário da Lagoa dos Patos submete-se a um regime de micro maré, com uma amplitude média de 0,47 m (GARCIA, 1997), sendo a maré mista, predominantemente do tipo diurna (FERNANDES *et al.*, 2005). Na região, a influência da maré tem importância secundária (MÖLLER *et al.*, 2009; MÖLLER; FERNANDES, 2010). Devido à morfologia entre a desembocadura e médio estuário, a energia da maré é reduzida por fricção em 80% (MÖLLER *et al.*, 2009; MÖLLER; FERNANDES, 2010).

A ação do vento e da descarga fluvial são os fatores principais de controle da hidrodinâmica lagunar (HARTMANN; SCHETTINI, 1991; MÖLLER; CASTAING, 1999; MÖLLER *et al.*, 2001; MÖLLER *et al.*, 2009; MÖLLER; FERNANDES, 2010). Durante os períodos de baixa descarga fluvial, o vento controla a circulação, enquanto que a descarga fluvial ganha destaque durante o pico de cheias anual, que ocorre no final do inverno (MÖLLER *et al.*, 2001).



Fonte dos dados: Base cartográfica do Instituto Brasileiro de Geografia e Estatística (IBGE), Imagem orbital Landsat 8 (221/082) - Banda 5 (United States Geological Survey - USGS). Sistema de coordenadas: UTM, 22S. MC 51°. Datum: WGS 1984. Elaborado por Marine Jusiane Bastos da Silva.

Figura 1.1 - Área de estudo - Lagoa dos Patos.

O regime dominante de ventos coincide com a orientação NE-SO do eixo principal da lagoa (MÖLLER *et al.*, 2001). Ventos de nordeste ocorrem 22% do ano com uma velocidade média de 3,6 a 5,1 m/s, enquanto ventos de sudoeste ocorrem 12% do ano com uma velocidade média de 5,4 a 8,2 m/s (GARCIA, 1998). Os ventos de sudoeste tornam-se mais importantes durante o outono e o inverno, por estarem associados aos sistemas frontais de origem polar (MÖLLER *et al.*, 2001).

A ação do vento, na hidrodinâmica da Lagoa dos Patos, está associada com as diferenças de nível entre a porção interna do corpo d’água e a região costeira, causadas pelo efeito local e não local (remoto) do vento (MÖLLER *et al.*, 2001; FERNANDES *et al.*, 2002). O efeito local do vento resulta da fricção do vento sobre a superfície da lagoa, enquanto que o efeito não local está relacionado à elevação ou ao rebaixamento do nível do mar na costa em virtude do transporte de Ekman (MÖLLER *et al.*, 2001). Agindo ventos de nordeste (sudoeste), há um rebaixamento (aumento) do nível na porção norte da lagoa e uma elevação (diminuição) do nível na parte sul, enquanto que na costa há um rebaixamento (aumento) do nível devido ao transporte de Ekman, promovendo a saída (entrada) de água no estuário (MÖLLER *et al.*, 2001).

O efeito local do vento é responsável pela maior parte das variações do nível nas partes central e norte da Lagoa dos Patos, contudo, é o efeito não local do vento que, gerando efeitos de *set up* e *set down* no oceano, controla as trocas de água entre a região estuarina e a plataforma continental (FERNANDES *et al.*, 2002). Em suma, o fluxo em direção ao mar está associado a ventos de nordeste, enquanto que o fluxo de enchente está relacionado ação de ventos de sudoeste (MÖLLER *et al.*, 2001; FERNANDES *et al.*, 2002).

No que diz respeito à descarga fluvial, os principais rios contribuintes para a laguna são o Guaíba e o rio Camaquã (MÖLLER *et al.*, 2001). A taxa média anual de descarga continental, através do estuário, é de cerca de 4.000 m^3/s, embora valores até 10.000 m^3/s possam ser observados durante eventos de El Niño (SEELIGER, 2001), fenômeno que provoca aumento da precipitação de chuvas na bacia de drenagem.

Os rios abrangidos pela bacia de drenagem da Lagoa dos Patos apresentam altas descargas no fim do inverno e início da primavera, seguido por baixas a moderadas descargas no verão e outono (CALLIARI *et al.*, 2008). Durante os períodos de alta descarga, a lagoa pode exportar água para o oceano durante meses, movendo a zona de mistura em direção às águas costeiras (MÖLLER *et al.*, 1991). A descarga fluvial superior a 3.000 m^3/s causa uma intensa estratificação da salinidade no estuário e valores superiores podem bloquear a entrada de água salgada na laguna (MÖLLER *et al.*, 1991; CALLIARI *et al.*, 2008; MÖLLER; FERNANDES, 2010).

As características hidrodinâmicas e morfológicas da laguna fazem com que a estratificação vertical seja dominante na circulação do estuário da Lagoa dos Patos (MÖLLER; CASTAING, 1999). Os altos níveis de descarga continental, a predominância de ventos de nordeste, a forma afunilada e a profundidade da desembocadura contribuem para essa característica (MÖLLER; CASTAING, 1999).

Os quatro modelos de circulação estuarina descritos por Cameron e Pritchard (1963) e Pritchard (1967) foram identificados no estuário da Lagoa dos Patos

(HARTMANN; SCHETTINI, 1991). A circulação estuarina pode mudar rapidamente, em horas, em virtude das condições meteorológicas na região da desembocadura (HARTMANN; SCHETTINI, 1991).

As baixas descargas no verão e no outono e a ação dos ventos de sudeste e sudoeste forçam a intrusão de água salgada na desembocadura, enquanto que os ventos de nordeste e as altas descargas reduzem a salinidade no estuário (FERNANDES *et al.*, 2005). Ademais, o alto fluxo de água doce e a ação constante de ventos do quadrante norte alinhados com o eixo da laguna são capazes de descaracterizar o ambiente estuarino, constituindo um sistema típico fluvial (HARTMANN; SCHETTINI, 1991).

A região estuarina recebe uma carga considerável de sedimentos finos (argila e silte) de origem fluvial, devido à alta precipitação de chuva na bacia de drenagem (CALLIARI *et al.*, 2008). A distribuição de sedimentos no estuário está relacionada à profundidade e à hidrodinâmica: sedimentos finos predominam em regiões profundas, enquanto areias dominam em regiões marginais rasas, mas também podem ser encontradas em canais onde se observa alta energia hidrodinâmica (CALLIARI, 1997; CALLIARI *et al.*, 2008).

1.3.2 Canal de acesso ao estuário da Lagoa dos Patos

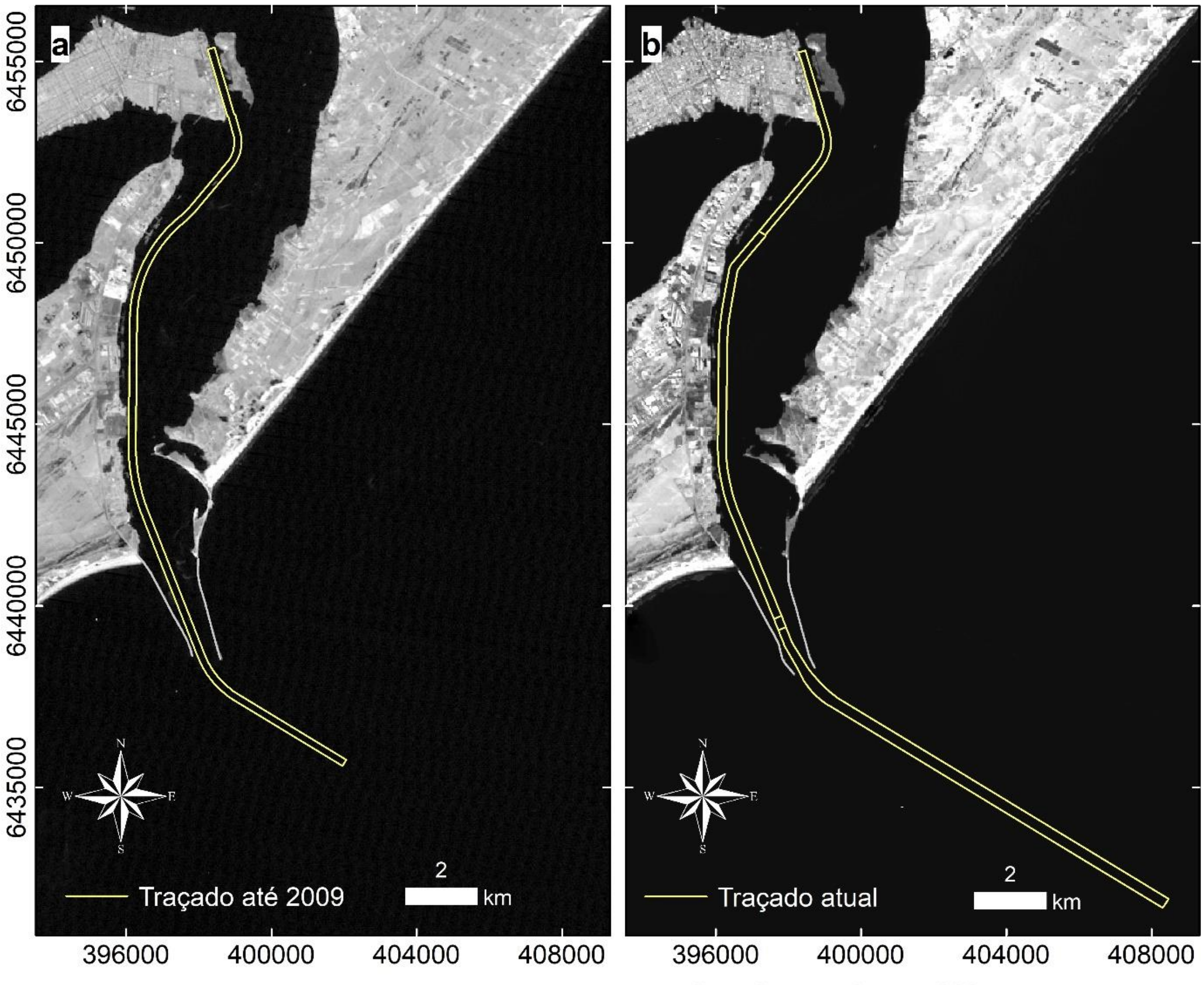
O canal de acesso ao estuário da Lagoa dos Patos é, também, o canal de acesso ao Porto do Rio Grande e a outros portos situados ao longo da Lagoa dos Patos, como os portos de Pelotas e Porto Alegre (Figura 1.2). Devido à sua orientação, também recebe a nomenclatura de Canal do Norte. O Porto do Rio Grande, um dos maiores do Brasil, tem sua infraestrutura localizada majoritariamente na margem oeste deste canal.

A instabilidade da profundidade e da direção dos canais da Barra do Rio Grande, no domínio marinho, foi um problema histórico para a navegação até a primeira década do século XX (CALLIARI *et al.*, 2010). Com a ação das ondas, consideráveis migrações do canal sobre a Barra do Rio Grande no sentido anti-horário (de sudoeste para nordeste) eram observadas (RODRIGUES, 1903 apud CALLIARI *et al.*, 2010). Os sedimentos tendiam a obstruir o canal e os fortes fluxos sazonais de vazante eram capazes de impedir essa obstrução (RODRIGUES, 1903 apud CALLIARI *et al.*, 2010).

No começo dos anos 1900, foram construídos dois molhes para fixar a desembocadura do estuário. O molhe leste foi construído nas adjacências do município do Rio Grande, na praia do Cassino, enquanto que o molhe leste foi situado junto ao município de São José do Norte, na praia do Mar Grosso.

O objetivo era que essa obra hidráulica acelerasse o fluxo da água em direção ao mar, transportando sedimentos, e permitindo, assim, que navios com calado maior que 3 m pudessem passar pelo local (MÖLLER; FERNANDES, 2010). Em sua configuração original, o molhe oeste (4.012 m) era menor que o molhe leste (4.250 m) (CUNHA; CALLIARI, 2009).

A configuração dos molhes permaneceu inalterada até 2009 (Figura 1.2a). Naquela configuração, o canal de acesso ao estuário era dragado para atingir a profundidade de 10,5 m nos setores do Porto Novo e 14 m no restante de sua extensão (Figura 1.6a).



Fonte dos dados:Imagens orbitais Landsat 8 (221/082), Banda 5 (United States Geological Survey, USGS) - (a) 2008 e (b) 2022. Sistema de coordenadas: UTM, 22S. MC 51°. Datum: WGS 1984. Elaborado por Marine Jusiane Bastos da Silva.

Figura 1.2: Canal de acesso ao estuário da Lagoa dos Patos (Canal de acesso ao Porto do Rio Grande). (a) Antes do aprofundamento do canal e da obra de extensão dos molhes; (b) Depois do aprofundamento do canal e da obra de extensão dos molhes.

Os investimentos realizados no Porto do Rio Grande no final dos anos 2000 foram voltados para uma obra de extensão dos molhes em direção ao oceano, associada à extensão e aprofundamento do canal de acesso (Figura 1.2b). Assim, o canal de acesso foi estendido em direção ao oceano e aprofundado, alcançando profundidades de 18 m nos setores 1, 2 e 3, de 16 m nos setores 4 e 5, e continuando com 10,5 m nos setores 6 e 7 (Figura 1.6b). A alteração na configuração dos molhes teve por intuito promover uma auto dragagem no sistema (SILVA *et al.*, 2015).

1.4 Estado da arte

A economia internacional está intimamente relacionada com as grandes infraestruturas costeiras, como portos e hidrovias (WANG; ANDUTTA, 2013). Cerca de 69% das maiores cidades do mundo estão localizadas em áreas costeiras e, sendo assim, o entendimento dos ambientes aquáticos, nele incluído o transporte de sedimentos, é de fundamental importância (WANG; ANDUTTA, 2013). Ainda nesse contexto, a evolução do transporte marítimo para acompanhar o crescente comércio internacional (PIANC, 2015), com maiores navios e maior capacidade de transporte, requer a adaptação dos ambientes costeiros para permitir a navegação de embarcações maiores (VAN MAREN *et al.*, 2015; PRUMM; IGLESIAS, 2016).

Devido às características naturais de abrigo, muitos portos do mundo estão situados em estuários, como os portos de Rotterdam, Antuérpia, Nova York, Hamburgo, Lisboa (PRUMM; IGLESIAS, 2016; FRANZEN *et al.*, 2023), sendo os estuários, assim, uma importante rota para o comércio internacional. Modificações no ambiente estuarino geralmente envolvem o aprofundamento de canais, aterros, construção de estruturas costeiras como molhes, cais e quebra-mares, entre outros (VAN MAREN *et al.*, 2015; FRANZEN *et al.*, 2021; ZHANG *et al.*, 2022), que promovem alterações no comportamento do ambiente, no que diz respeito à hidrodinâmica, ao transporte de sedimentos, e a outros aspectos.

Em canais de navegação, a dinâmica de sedimentos requer destaque, visto que o assoreamento é um dos principais aspectos a ser observado. Geralmente, o assoreamento está associado justamente às condições hidrodinâmicas de menor energia requeridas para áreas portuárias, como as que são proporcionadas pelos estuários (WINTERWERP, 2005; VAN RIJN, 2016).

Os sedimentos são transportados pelo fluxo e são depositados quando o fluxo perde a capacidade de transportá-los (WINTERWERP, 2005). O assoreamento ocorre em áreas onde as condições hidrodinâmicas permitem a deposição e esse processo pode limitar a navegação, tornando-se um fator de risco e reduzindo a acessibilidade à infraestrutura portuária (HUGUET *et al.*, 2020).

A evolução ao longo do tempo do canal de navegação demonstra a resposta morfológica da interação de diferentes fatores que controlam a dinâmica de sedimentos como a geometria do canal, as características do sedimento, a circulação estuarina e as intervenções antrópicas. Em canais portuários, as taxas de sedimentação variam devido às variações temporais e espaciais desses fatores (e.g., RESTREPO *et al.*, 2020; RAHMAN; ALI, 2022).

Um dos métodos mais conhecidos e difundidos para remover sedimentos do leito e, assim, manter o acesso, é a dragagem (BIANCHINI *et al.*, 2019; KIRICHEK *et al.*, 2021), que compõe um dos principais custos operacionais de um porto. Embora as operações de dragagem permitam atingir as profundidades locais desejadas, elas não são capazes de garantir a prevenção do assoreamento ao longo do tempo e podem ser altamente ineficientes, uma vez que precisam ser realizadas regularmente (HUGHET *et al.*, 2020; KIRICHEK *et al.*, 2021).

O assoreamento pode ser minimizado aumentando a velocidade no canal para manter o sedimento em movimento (*keep sediment moving*) ou reduzindo a concentração de sedimentos em suspensão que chegam ao canal para manter o sedimentos fora da área (*keep sediment out*) (HEADLAND *et al.*, 2007). Outras estratégias para manutenção de profundidades, com menores custos e menos impactos negativos ao ambiente, também podem compor o rol de possíveis soluções mais sustentáveis (BIANCHINI *et al.*, 2019).

O desenvolvimento de estratégias para redução do assoreamento requer um entendimento detalhado dos processos de deposição dos sedimentos e, ainda, deve considerar o meio ambiente e sua interação com o *layout* da infraestrutura portuária (HUGUET *et al.*, 2020). Além disso, os canais e as infraestruturas portuárias estão localizados em ambientes diversos e diferentes atores estão envolvidos ou, ainda, predominam em cada região (WINTERWERP, 2005). A investigação da evolução morfológica dos canais de navegação contribui para uma melhor compreensão dos padrões de sedimentação e contribui na busca por estratégias para minimizar o assoreamento.

Diversos estudos vem sendo desenvolvidos para compreender a dinâmica de sedimentos de portos localizados em estuários (PONTEE *et al.*, 2004; WINTERWERP, 2005; CATTANI; LAMOUR, 2016; MAYERLE *et al.*, 2015; SILVA *et al.*, 2015; VAN RIJN, 2016; HUA *et al.*, 2020; MATHEW; WINTERWERP, 2020; RESTREPO *et al.*, 2020; ÁVILA; GALLO, 2021; DA SILVA *et al.*, 2022). Nesse ínterim, a análise de dados batimétricos é capaz de prover grandes avanços no entendimento da evolução ao longo do tempo e do espaço da morfologia dos canais, suas características e dos processos de sedimentação (e.g. MONGE-GANUZAS *et al.*, 2013; CATTANI; LAMOUR, 2016; ZHU *et al.*, 2019; RESTREPO *et al.*, 2020; RAHMAN; ALI, 2022; YANG *et al.*, 2019; ZHANG *et al.*, 2022).

Para o estuário da Lagoa dos Patos, onde está situado o único canal de acesso à laguna e aos portos localizados ao longo de sua extensão, estudos relevantes foram desenvolvidos para entender a hidrodinâmica, a dinâmica de sedimentos, a circulação estuarina e outros aspectos do ambiente (e.g. CALLIARI, 1980; LONG; PAIM, 1987; HARTMANN; SCHETTINI, 1991; MÖLLER *et al.*, 2001; FERNANDES *et al.*, 2002; ANTIQUEIRA; CALLIARI, 2005; FERNANDES *et al.*, 2005; CUNHA; CALLIARI, 2009; CALLIARI *et al.*, 2008; BARROS *et al.*, 2014; SILVA *et al.*, 2015; MARTELO *et al.*, 2019a; TÁVORA *et al.*, 2019; ANTÓNIO *et al.*, 2020; BITENCOURT *et al.*, 2020; IVANOFF *et al.*, 2020; DA SILVA *et al.*, 2022; FRANZEN *et al*., 2023). Além disso, os impactos de dragagens na região também vêm sendo discutidos (MARTELO *et al.*, 2019b; CALLIARI *et al.*, 2020; FERNANDES *et al.*, 2021). No que diz respeito à dinâmica de sedimentos, especialmente, à deposição de sedimentos no canal de acesso ao estuário da Lagoa dos Patos, há grande carência de pesquisas.

Há ainda maior escassez de pesquisas quando consideram-se aquelas realizadas com base em dados medidos *in situ*, fato que pode estar relacionado tanto aos custos quanto às dificuldades de encontrar esses dados. Bastos da Silva (2016, 2019) iniciou o estudo da dinâmica de sedimentos considerando dados de levantamentos batimétricos fornecidos pela Autoridade Portuária a fim de investigar a evolução do fundo do canal em relação a profundidades de projeto, trazendo importantes resultados com enfoque voltado para engenharia.

Neste contexto, por meio do alcance aos objetivos propostos, a presente tese busca preencher algumas lacunas no entendimento dos processos sedimentares no canal de acesso ao estuário da Lagoa dos Patos, que ainda não foram alvo de pesquisas científicas. Busca-se entender aspectos relacionados à evolução do canal ao longo do tempo e do espaço e identificar padrões nesses comportamentos, apoiando-se, para isso, em dados disponibilizados para esse estudo e medidos i*n situ* ao longo de aproximadamente 20 anos.

1.5 Materiais e métodos

O objetivo desta seção é apresentar a metodologia abordada para o desenvolvimento desta tese. Apresenta-se, assim, os aspectos relacionados ao tratamento dos dados propriamente dito, conforme exposto nos itens 1.5.1 e 1.5.2. O esquema apresentado na Figura 1.3 apresenta uma descrição resumida dos procedimentos realizados.

1.5.1 Dados batimétricos

Caracterização e padronização dos dados

Os dados de levantamentos batimétricos foram fornecidos pela Autoridade Portuária (empresa pública Portos RS), assim como, dados do histórico de dragagens realizados em cada setor do canal. Os dados compreendem o período entre os anos de 2001 e 2020, porém não foram medidos em intervalos regulares de tempo e apresentam área de cobertura variável. Os dados foram fornecidos majoritariamente em formato .dwg (*software* AutoCAD). Os demais encontravam-se em formato .xyz.

Inicialmente, os dados contidos em arquivos .dwg foram exportados para o formato .xyz. Ademais, foram identificadas as seguintes informações de cada levantamento: período de sondagem, área de abrangência, sistema de referência e referencial vertical.

Em relação ao referencial vertical, as sondagens apresentam a informação de que a referência vertical foi o nível de redução (NR) da Diretoria de Hidrografia e Navegação (DHN) para o local. Além disso, observou-se que os levantamentos foram realizados utilizando sinal sonoro de alta frequência, conforme exigência da Autoridade Marítima (DIRETORIA DE HIDROGRAFIA E NAVEGAÇÃO, 2017). A grande maioria dos dados foi coletada utilizando tecnologia monofeixe, com medições em seções transversais ao eixo do canal espaçadas a cada 50 m. Entretanto, em levantamentos mais recentes a tecnologia multifeixe foi utilizada.

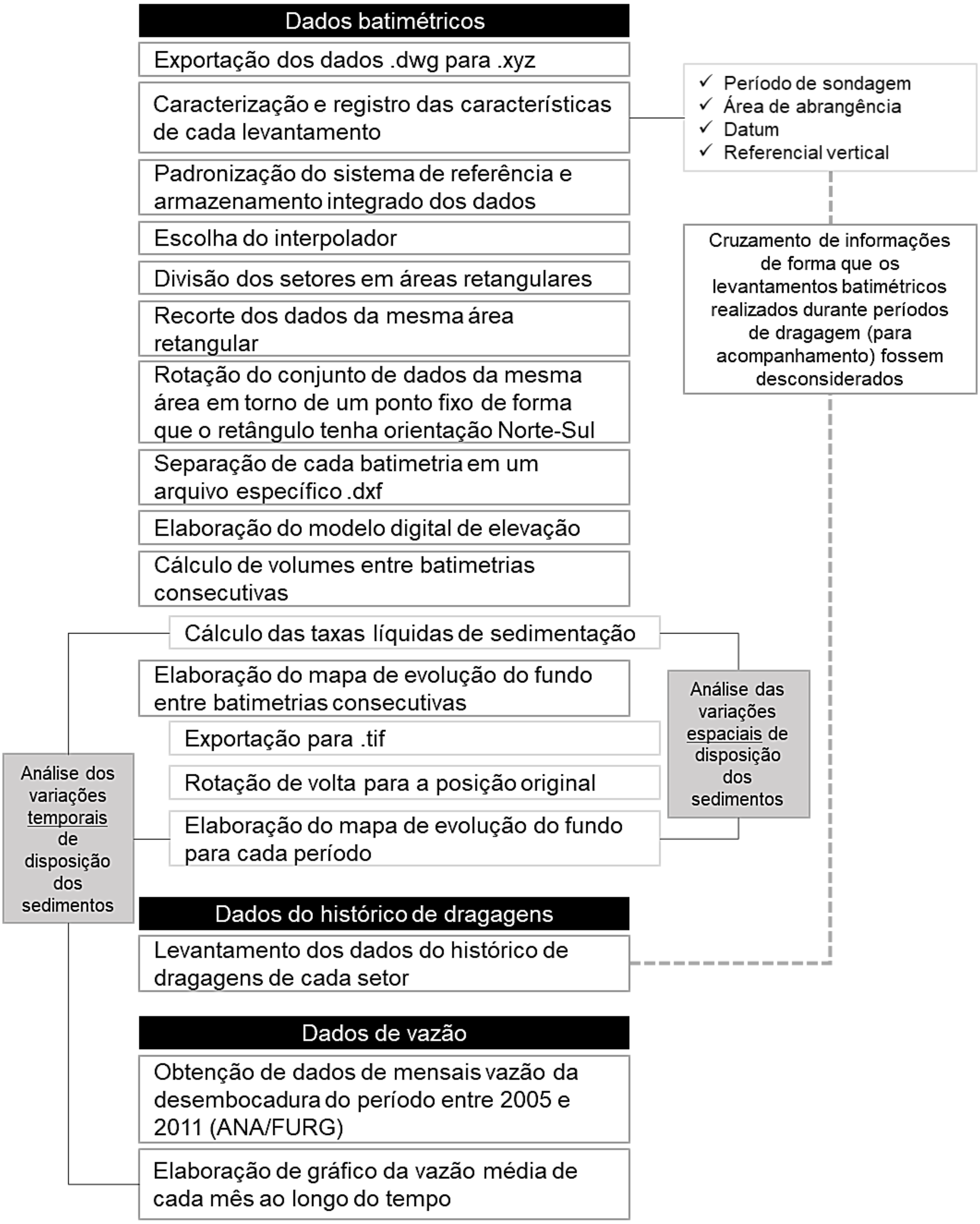


Figura 1.3: Representação esquemática dos materiais e métodos.

Quanto ao sistema de coordenadas, todos os levantamentos apresentavam sistema de coordenadas Universal Transverso de Mercator (UTM), Zona 22 Sul, com coordenadas em metros. Os levantamentos batimétricos estavam referenciados a três sistemas de referência diferentes: *datum* Arbitrário, Córrego Alegre e World Geodetic System 1984 (WGS 1984), sendo os dois primeiros em sondagens mais antigas e o último em sondagens mais recentes. Conforme informação constante nos levantamentos, o datum Arbitrário foi criado especificamente para levantamentos da região do Porto do Rio Grande.

O sistema de referência adotado como padrão foi o WGS 1984 e todos os dados foram transformados para esse sistema. Conforme informação constante nos arquivos, a transformação do datum Arbitrário para o datum Córrego Alegre foi feita adicionando-se +112,47 m nas coordenadas leste (x) e +115,47 m na coordenada norte (y). Em seguida, todos dados referenciados em relação ao datum Córrego Alegre foram, então, transformados para WGS 1984 por meio de procedimento no *software* SURFER 13. Após a padronização do sistema de referência, todos os dados foram inseridos em um arquivo único .dwg, tendo cada levantamento batimétrico uma camada exclusiva.

Escolha do interpolador

A escolha do interpolador krigagem foi baseada na análise de interpoladores realizada por Bastos da Silva (2016). Em seu estudo, a autora comparou os modelos digitais de elevação gerados no *software* SURFER empregando cinco tipos diferentes de interpoladores: triangulação com interpolação linear, krigagem, inverso ponderado pela distância, vizinho natural e vizinho mais próximo.

Conforme a literatura disponível, Bastos da Silva (2016) verificou que o método triangulação com interpolação linear é o que apresentava maior fidelidade aos dados originais. Entretanto, observou que, ao serem gerados modelos digitais de elevação utilizando esse método, havia determinados nós da grade em que o *software* não era capaz de interpolar um valor, atribuindo-o um valor incoerente (da ordem de 10^{38}).

Dessa forma, a autora correlacionou os demais métodos ao método de interpolação triangulação com interpolação linear (Figura 1.4) e elencou que duas condições que embasariam sua escolha de interpolador: (i) que o interpolador gerasse a coordenada Z em todos os pontos da grade, e (ii) que apresentasse o maior coeficiente de correlação com o método de triangulação com interpolação linear. Baseada nessas condições, Bastos da Silva (2016) observou que o interpolador krigagem era o que satisfazia a essas condições.

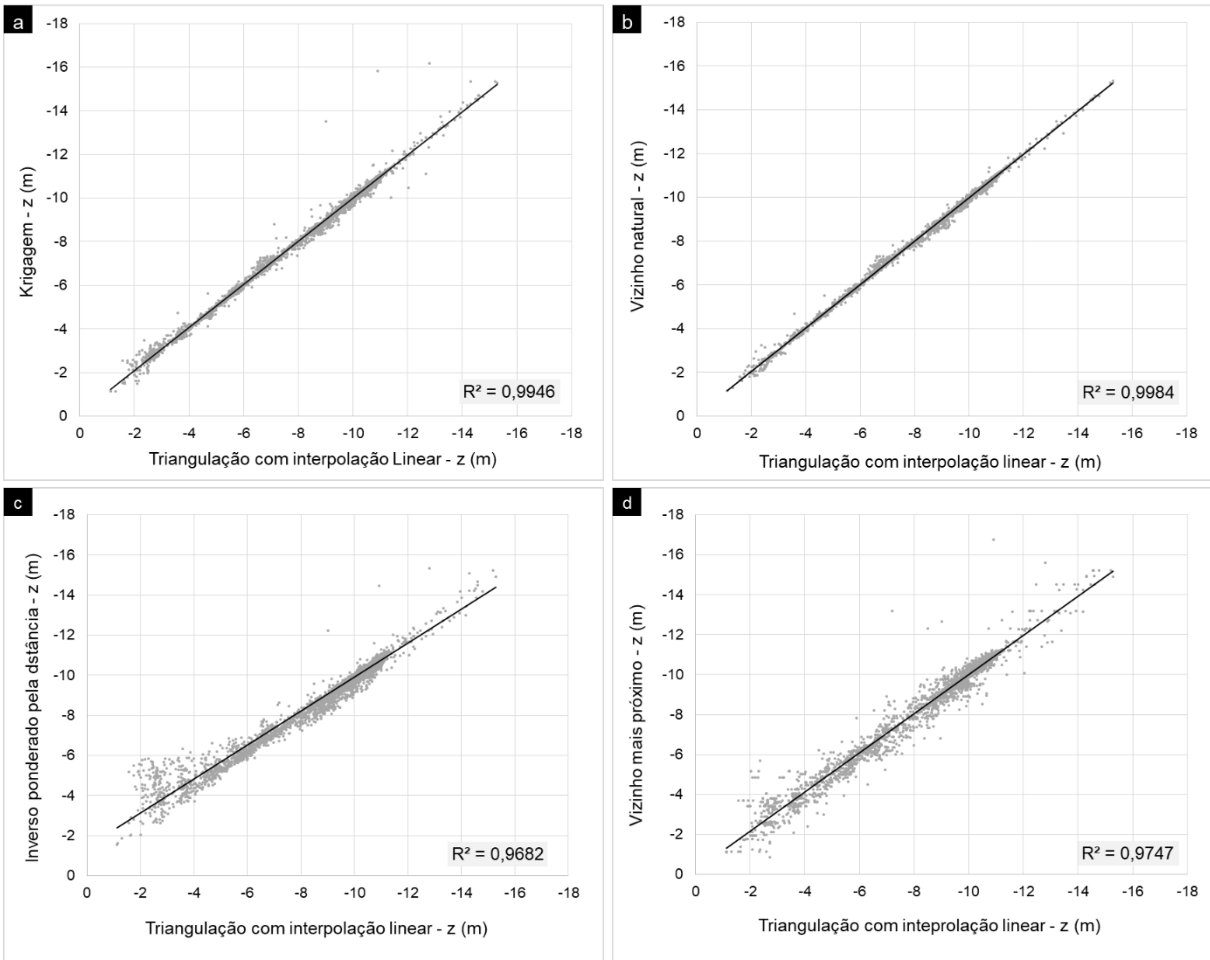


Figura 1.4: Escolha do interpolador. Fonte: Bastos da Silva (2016), adaptado.

Divisão da área de estudo em retângulos e elaboração dos MDEs

No *software* SURFER, a krigagem é um método de interpolação que cria grades retangulares, cujos nós estão distribuídos em linhas horizontais e colunas verticais. Considerando uma porção do canal cujo eixo central possua alguma orientação em relação ao norte, observou-se que o método extrapolava valores para além dos limites definidos pela batimetria, a fim de completar a grade retangular (Figura 1.5b).

Sendo assim, tendo em vista a curvatura do canal, optou-se pela seguinte sequência de procedimentos: (i) dividir o canal curvilíneo em áreas retangulares, delimitando o conjunto de dados (Figura 1.5a,b); (ii) excluir os pontos dos levantamentos batimétricos localizados fora desse limite (Figura 1.5a,b); (iii) selecionar todo o conjunto de dados e rotacioná-lo em torno de um vértice fixo, de forma que a base do retângulo ficasse na horizontal e, consequentemente, seu comprimento ficasse vertical (Figura 1.5c); (iv) exportar cada levantamento batimétrico deste retângulo e deste conjunto de dados para um arquivo individual; (v) gerar o modelo digital de elevação no *software* SURFER utilizando essa configuração rotacionada; (vi) rotacionar o modelo digital de elevação de volta para sua configuração original com base no valor do ângulo θ e do vértice fixo (Figura 1.5d).

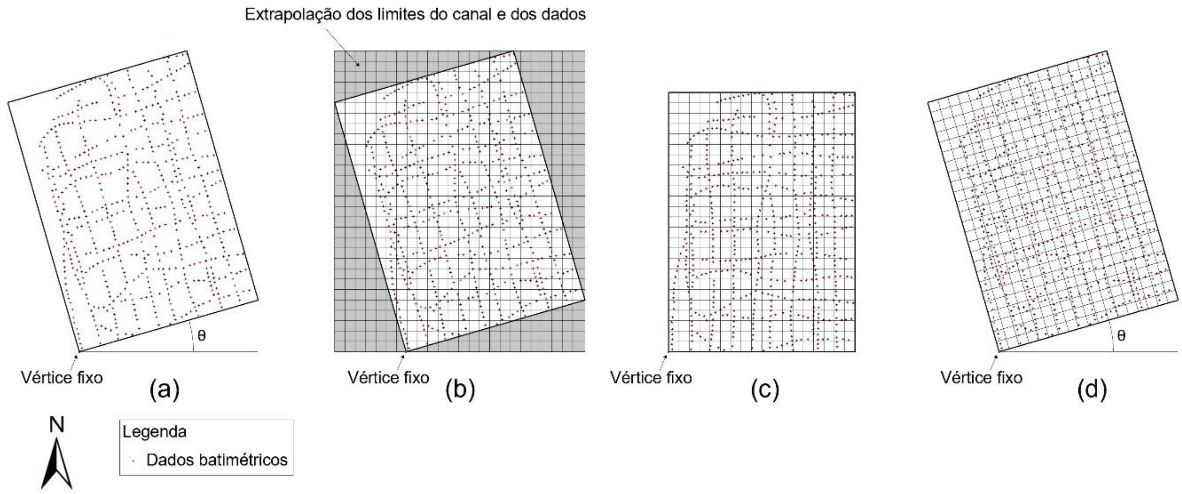
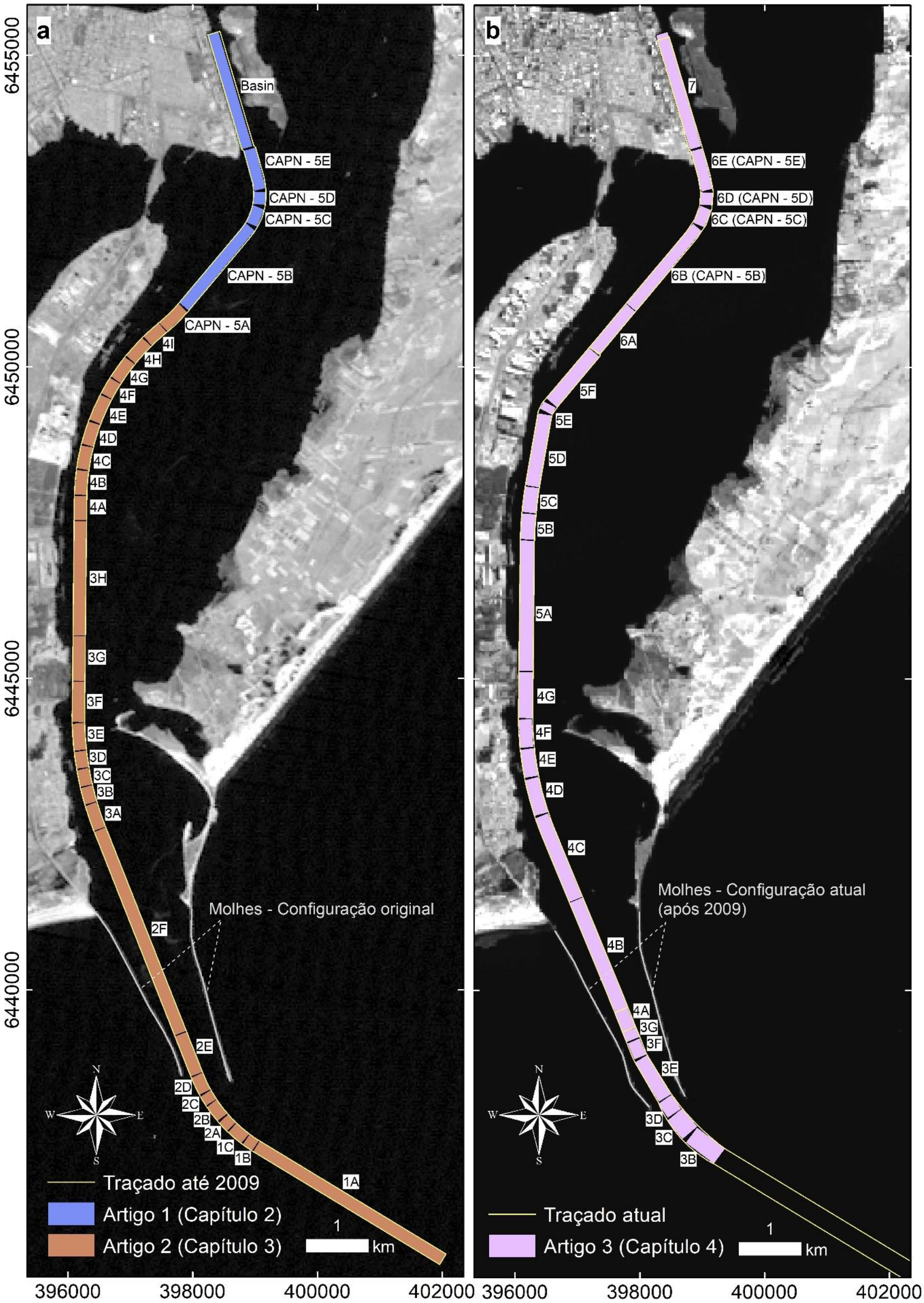


Figura 1.5: Descrição da metodologia, conforme Bastos da Silva (2016). (a) Dados batimétricos confinados à área retangular; (b) Grade gerada considerando a posição original do conjunto de dados, apresentando pontos fora dos limites do retângulo e, portanto, do canal (áreas em cinza); (c) Grade gerada após a rotação do retângulo e seu conjunto de dados, limitada à área de interesse, sem extrapolação; (d) Rotação da grade para a posição original, após elaboração do MDE.

Além da própria questão de necessidade para aplicação do método, a divisão do canal em retângulos considerou os seguintes aspectos: (i) a orientação do canal, isto é, a cada mudança de orientação, um novo retângulo era criado; (ii) a área contida no mesmo retângulo pertencia ao mesmo trecho, conforme a divisão da Autoridade Portuária; (iii) a área contida no mesmo retângulo possuía a mesma profundidade de projeto; (iv) o retângulo possuir dimensões múltiplas de dez (10), visto que a largura do canal tem essa característica em ambos cenários.

A configuração anterior aos anos de 2009/2010 foi dividida em 32 retângulos (Figura 1.6a), enquanto que a configuração posterior foi dividida em 25 retângulos (Figura 1.6b). O número menor de retângulos no segundo cenário é justificado pelo fato de que não foi contemplado todo o canal de navegação, devido à abrangência reduzida dos dados disponíveis. As coordenadas dos vértices dos retângulos dos cenários anterior a 2009/2010 e atual estão apresentadas nas tabelas Tabela 1.1 e Tabela 1.2, respectivamente.



Fonte dos dados:Imagens orbitais Landsat 8 (221/082), Banda 5 (United States Geological Survey, USGS) - (a) 2008 e (b) 2022. Sistema de coordenadas: UTM, 22S. MC 51°. Datum: WGS 1984. Elaborado por Marine Jusiane Bastos da Silva.

Figura 1.6: Divisão da região de estudo em retângulos para atendimento à metodologia proposta e delimitação espacial dos artigos que compõem a tese. (a) Cenário anterior aos anos de 2009 e 2010. (b) Cenário atual. Coordenadas em m.

Tabela 1.1: Coordenadas UTM (m) dos vértices dos retângulos do cenário anterior aos anos de 2009/2010 (Figura 1.6a).

Retângulo	Coord.	Vértice 1	Vértice 2	Vértice 3	Vértice 4
1A	E	402058,8557	401955,0312	398963,5815	399067,4060
	N	6437761,1699	6435590,2299	6437407,1583	6437578,0983
1B	E	399065,8838	398952,7922	398796,0845	398909,1761
	N	6437578,6995	6437413,7441	6437521,1811	6437686,1365
1C	E	398904,6370	398774,3738	398561,9079	398692,1711
	N	6437682,9725	6437531,2112	6437713,5797	6437865,3410
2A	E	398691,8405	398549,7036	398416,0366	398558,1735
	N	6437871,5378	6437730,8357	6437865,8658	6438006,5680
2B	E	398555,7467	398396,4049	398221,1396	398380,4814
	N	6438011,0294	6437890,1567	6438121,2023	6438242,0750
2C	E	398382,6208	398214,3928	398117,0457	398285,2736
	N	6438243,6447	6438135,4812	6438286,8864	6438395,0499
2D	E	398282,7349	398101,6541	397970,0432	398151,1240
	N	6438395,2323	6438310,3221	6438590,9973	6438675,9075
2E	E	398154,3147	397967,9589	397713,8407	397900,1965
	N	6438677,1665	6438604,5613	6439256,8066	6439329,4118
2F	E	397896,4434	397710,4050	396418,3071	396664,3455
	N	6439337,3730	6439263,9584	6442538,2343	6442611,6490
3A	E	396601,7411	396413,4305	396268,5787	396456,8893
	N	6442614,2436	6442546,8707	6442951,7385	6443019,1114
3B	E	396463,8395	396271,0355	396196,6028	396389,4067
	N	6443022,6440	6442969,4777	6443239,4032	6443292,5694
3C	E	396391,8899	396196,4983	396136,7376	396332,1292
	N	6443295,5072	6443252,8210	6443526,3693	6443569,0555
3D	E	396334,0007	396135,9807	396096,6787	396294,6987
	N	6443571,5014	6443543,4285	6443820,6565	6443848,7294
3E	E	396295,4139	396096,0180	396061,8450	396261,2409
	N	6443850,8562	6443835,3230	6444273,9939	6444289,5271
3F	E	396268,6818	396068,6820	396069,6918	396269,6916
	N	6444292,4721	6444292,7781	6444952,7773	6444952,4713
3G	E	396269,7947	396069,8196	396081,3283	396281,3034
	N	6444953,7262	6444956,8793	6445686,7886	6445683,6355
3H	E	396277,0092	396077,0230	396098,6965	396298,6826
	N	6445684,9249	6445687,2807	6447527,1531	6447524,7973
4A	E	396297,0114	396097,0179	396100,2434	396300,2369
	N	6447533,8588	6447535,4716	6447935,4586	6447933,8458
4B	E	396301,4731	396102,0002	396131,0221	396330,4950
	N	6447933,9716	6447948,4825	6448347,4283	6448332,9173
4C	E	396333,5936	396136,9661	396206,4562	396403,0837
	N	6448334,8525	6448371,4262	6448745,0184	6448708,4447
4D	E	396405,6459	396214,3170	396324,9955	396516,3243
	N	6448708,4450	6448766,6968	6449130,2216	6449071,9698
4E	E	396520,2901	396337,2643	396514,6554	396697,6812
	N	6449075,6133	6449156,2456	6449558,9023	6449478,27
4F	E	396700,5077	396527,1514	396671,7710	396845,1273
	N	6449477,2661	6449577,0038	6449828,3704	6449728,6328
4G	E	396846,1044	396683,4685	396910,4535	397073,0894
	N	6449729,5038	6449845,9064	6450163,0464	6450046,6439
4H	E	397073,9920	396925,6753	397187,3111	397335,6277
	N	6450046,8267	6450180,9989	6450470,2164	6450336,0442

4I	E	397937,6402	397205,4359	397453,0571	395785,2614
	N	6450339,1665	6450489,2400	6450707,3770	6450557,3035
5A CAPN	E	397591,5271	395474,4264	397919,1584	397782,0577
	N	6450563,3534	6450708,9673	6450871,8298	6451017,4437

Tabela 1.2: Coordenadas UTM (m) dos vértices dos retângulos do cenário atual (Figura 1.6b).

Retângulo	Coord.	Vértice 1	Vértice 2	Vértice 3	Vértice 4
3B	E	399183,0392	399369,514	398914,17	398727,6952
	N	6437213,5093	6437461,1525	6437804,0255	6437556,3823
3C	E	398681,2274	398925,6337	398673,8929	398429,4867
	N	6437609,1312	6437815,6877	6438113,5578	6437907,0013
3D	E	398444,3194	398667,5237	398509,9764	398286,7722
	N	6437950,5648	6438102,4854	6438333,9565	6438182,0359
3E	E	398300,0121	398504,7052	398113,1343	397908,4413
	N	6438205,4735	6438330,7762	6438970,4419	6438845,1392
3F	E	397905,8444	398108,8308	397997,0063	397794,0199
	N	6438885,3419	6438970,1742	6439237,7472	6439152,9148
3G	E	397784,3584	397997,8097	397934,4919	397721,0406
	N	6439166,0269	6439251,6922	6439409,4606	6439323,7953
4A	E	397721,5194	397933,0479	397799,548	397588,0195
	N	6439326,5621	6439416,8709	6439729,5652	6439639,2565
4B	E	397597,1073	397809,5942	397078,561	396866,074
	N	6439645,2945	6439733,3247	6441497,8899	6441409,8597
4C	E	396864,4756	397077,5117	396527,2015	396314,1654
	N	6441411,8548	6441498,5475	6442850,8636	6442764,1709
4D	E	396305,6895	396527,8986	396373,0575	396150,8484
	N	6442796,0626	6442855,4183	6443435,0943	6443375,7386
4E	E	396145,0183	396372,7083	396307,6776	396079,9876
	N	6443408,4954	6443441,0108	6443896,3909	6443863,8755
4F	E	396076,5857	396296,291	396272,4916	396052,7862
	N	6443892,1097	6443903,4921	6444362,876	6444351,4937
4G	E	396051,8722	396281,862	396288,919	396058,9292
	N	6444367,143	6444364,9789	6445114,9457	6445117,1098
5A	E	396059,319	396289,3088	396309,0686	396079,0788
	N	6445127,1996	6445125,0354	6447224,9424	6447227,1066
5B	E	396078,1041	396307,6391	396334,3343	396104,7994
	N	6447242,9188	6447228,3	6447647,4508	6447662,0696
5C	E	396105,8087	396334,1314	396384,7616	396156,4389
	N	6447678,4701	6447650,744	6448067,6812	6448095,4072
5D	E	396158,7955	396385,2952	396590,3761	396363,8764
	N	6448108,4387	6448068,4653	6449230,5074	6449270,4808
5E	E	396389,9287	396594,1844	396658,544	396454,2884
	N	6449337,9778	6449232,2441	6449356,5736	6449462,3073
5F	E	396493,2933	396669,7989	397355,829	397179,3234
	N	6449502,2759	6449354,8115	6450175,9465	6450323,4109
6A	E	397185,3536	397337,9214	397932,7828	397780,215
	N	6450321,3411	6450192,0233	6450893,8352	6451023,1529
6B	E	397779,1387	397933,0015	398999,9159	398846,0531
	N	6451029,0702	6450901,296	6452186,0503	6452313,8245
6C	E	398849,047	399033,8592	399152,3552	398967,543
	N	6452317,2177	6452240,7687	6452527,2275	6452603,6766
6D	E	398963,9005	399163,6761	399173,6214	398973,8458
	N	6452607,0415	6452597,5698	6452807,3342	6452816,8059
6E	E	398981,6885	399175,5278	399008,0513	398814,212
	N	6452816,6073	6452865,8651	6453524,9187	6453475,6609
7	E	398795,9556	398987,7444	398443,2406	398251,4518
	N	6453490,148	6453546,8672	6455388,0395	6455331,3204

É importante ressaltar que os retângulos da porção ao norte do canal não sofreram alteração e possuem os mesmos limites em ambos cenários, sendo eles no cenário anterior a 2009 e atual, respectivamente: CAPN-5E e 6E; CAPN – 5D e 6D; CAPN – 5C e 6C, CAPN – 5B e 6B. Os limites do setor da bacia do Porto Novo (setor 7) foram estendidos para abranger uma maior parte da região no segundo cenário, visto que a cobertura dos dados batimétricos desse local era mais abrangente. A mudança de configuração geométrica do canal ocorreu a partir do setor sul do Canal de Acesso ao Porto Novo do Rio Grande, que corresponde ao retângulo CAPN-5A no cenário anterior a 2009/2010 e ao retângulo 6A no cenário atual.

Os modelos digitais de elevação (MDEs) foram gerados para uma grade contendo nós espaçados por 10 m, tanto na vertical quanto na horizontal. Devido ao procedimento aplicado, as linhas dos MDEs ficaram perpendiculares ao eixo do canal na respectiva área retangular, enquanto que as colunas ficaram paralelas.

Cálculo das taxas líquidas de sedimentação

A comparação entre dois modelos digitais de elevação gerados a partir de levantamentos batimétricos diferentes correspondentes à mesma área retangular foi realizada considerando-se o levantamento mais antigo como referência. Volumes acima dessa referência eram considerados deposição, isto é, sedimentos foram depositados naquele local (volumes positivos) no dado intervalo de tempo. Volumes abaixo dessa referência eram considerados erosão, ou seja, sedimentos foram removidos daquele local (volumes negativos) no intervalo de tempo.

A taxa líquida de sedimentação (T) para cada retângulo e para cada período entre levantamentos batimétricos foi calculada por meio da seguinte fórmula:

$$\mathrm{T} = \frac{\mathrm{V_{líquido}}}{\mathrm{A_{retângulo}} \cdot \mathrm{t}} \cdot 100$$

Sendo:

T = taxa líquida de sedimentação, em cm/mês;

$\mathrm{V_{líquido}}$ = a diferença entre o volume depositado (positivo) e o volume erodido (negativo), em m³;

$\mathrm{A_{retângulo}}$ = a área plana do retângulo correspondente, em m²;

t = o tempo decorrido entre os dois levantamentos batimétricos utilizados para elaboração dos respectivos MDEs, em meses.

O tempo decorrido entre os levantamentos batimétricos foi calculado tomando-se como referência o último dia do período de aquisição dos dados de ambos casos. Por exemplo, o levantamento batimétrico da bacia do Porto Novo (chamada de *Basin* e apresentado no artigo 1) referente ao mês de maio de 2007 foi finalizado em 17 de maio de 2007 e o levantamento batimétrico da mesma região de maio de 2009 foi finalizado em 02 de maio de 2009. Nesse caso, o tempo decorrido entre os dois levantamentos batimétricos é de 716 dias, o que equivale a 23,87 meses, considerando que um (01) mês equivale a 30 dias.

Os valores obtidos para as taxas líquidas de sedimentação foram representados em gráficos, tendo no eixo das abscissas os retângulos e o correspondente valor da taxa no eixo das ordenadas.

Elaboração de mapas de evolução do fundo

Os mapas de evolução do fundo foram elaborados por meio da subtração da coordenada Z (profundidade) dos MDEs entre dois levantamentos batimétricos de interesse. Todos os MDEs correspondentes a um mesmo retângulo foram gerados com os mesmos limites, com o mesmo número de nós e com mesmo espaçamento entre os nós da grade, tendo, portanto, uma malha padrão para cada área retangular. Sendo assim, nesta etapa, subtraiu-se os valores de Z correspondentes ao mesmo nó de dois MDEs, tendo o MDE correspondente à data mais antiga como referência. Obteve-se, assim, um valor de ΔZ (variação de profundidade) para cada nó.

Para o artigo 1 (Capítulo 2), o padrão adotado foi o seguinte: valores de $\Delta Z>0{,}25$ m foram considerados deposição e representados em tons de vermelho; valores de $\Delta Z<-0{,}25$ m foram considerados erosão e representados em tons de azul. O intervalo de valores entre $-0{,}25$ m$<\Delta Z<0{,}25$ m foi considerado como estabilidade, representado em branco.

Para os artigos 2 e 3 (Capítulos 3 e 4), o padrão adotado foi o seguinte: valores de $\Delta Z>0{,}50$ m foram considerados deposição e representados em tons de vermelho; valores de $\Delta Z<-0{,}50$ m foram considerados erosão e representados em tons de azul. O intervalo de valores entre $-0{,}50$ m$<\Delta Z<0{,}50$ m foi considerado como estabilidade, representado nas cores vermelho e azul com um nível de transparência, para que se pudesse visualizar o comportamento do fundo mesmo em locais considerados estáveis.

A mudança do padrão adotado dos padrões nos artigos se deu em decorrência da mudança de profundidade de projeto encontrada em cada um deles: no artigo 1, o ambiente delimitado tem profundidade de projeto de 10,5 m; no artigo 2, o ambiente delimitado tem profundidade de projeto de 14 m; já no artigo 3 as profundidades variam entre 10,5 m, 16 m e 18 m, isto é, aumentam.

1.5.2 Dados de vazão

Dados de descarga média mensal da desembocadura da Lagoa dos Patos foram utilizados a fim de analisar conectadamente os valores de taxas líquidas de sedimentação e a intensidade de vazão no mesmo período. Os dados foram obtidos por meio da Agência Nacional de Águas e Saneamento Básico (ANA), uma vez que se encontravam disponíveis para acesso no Portal HidroWeb, ferramenta integrante do Sistema Nacional de Informações sobre Recursos Hídricos (SNIRH), no sítio eletrônico *https://www.snirh.gov.br/hidroweb/serieshistoricas*.

Os dados disponíveis compreendiam o período entre agosto de 2005 e dezembro de 2011 e foram medidos no ponto de coordenadas 32,14° S e 52,10° W. Nesse intervalo de tempo, dados do período entre agosto de 2009 e abril de 2010 e do mês de maio de 2011 não estavam disponíveis.

Conforme informação disponível no Portal, a responsável pela operação dos dados é a Universidade Federal do Rio Grande (FURG). Sendo assim, informações foram solicitadas à FURG e os seguintes esclarecimentos foram prestados: valores positivos de vazão indicam enchente e valores negativos de vazão indicam vazante (devido a orientação Norte-Sul do canal), e a unidade de medida dos dados é m^3/s.

Com base nessas informações, os dados de vazão média mensal foram dispostos em um gráfico de barras, com eixo das abscissas contendo o mês de referência e o eixo das ordenadas contendo a respectiva vazão mensal. Valores positivos indicam enchente e valores negativos indicam vazante.

1.6 Delimitação espacial e temporal de cada artigo

A delimitação da abrangência de cada artigo se deu em função de aspectos espaciais e temporais.

No artigo 1, apresentado no Capítulo 2 desta tese, considerou-se a região da bacia e do canal de acesso ao Porto Novo e limitou-se espacialmente até o retângulo

CAPN – 5B no cenário anterior a 2009/2010 (mesmo que 6B no cenário pós 2009/2010), pois, a partir desta região, ocorreu uma mudança na configuração do traçado do canal após os anos de 2009 e 2010. Delimitou-se espacialmente o artigo para investigar a região que permaneceu inalterada e analisou-se dados disponíveis para o período entre 2001 e 2018. Os retângulos compreendidos neste artigo estão destacados em tom azul na Figura 1.6a.

No artigo 2, apresentado no Capítulo 3 desta tese, o restante do canal em sua configuração anterior a 2009/2010 foi analisado. Por isso, os dados foram limitados temporalmente entre os anos de 2005 e 2009. Os retângulos compreendidos neste artigo estão destacados em tom marrom na Figura 1.6a.

No artigo 3, apresentado no Capítulo 4 desta tese, considerou-se o traçado atual do canal. A região da bacia do Porto Novo foi alargada de forma a abranger pontos de levantamentos batimétricos nessas regiões contemplados nos levantamentos batimétricos mais recentes. Sendo assim, o artigo abrangeu dados do período entre os anos 2015 e 2020 e se limitou à porção de cobertura desses dados, não sendo possível a abrangência de todo o canal, limitando-se aos trechos internos e à região da desembocadura. A análise foi iniciada com base em dados do ano de 2015 pois, embora outros levantamentos batimétricos referentes ao período entre os anos de 2010 e 2015 estivessem disponíveis, suas datas coincidiam com períodos de dragagem. Assim, foram desconsiderados, visto que o objetivo deste trabalho é analisar apenas as variações do fundo promovidas naturalmente, sem intervenção humana. Os retângulos compreendidos neste artigo estão destacados em lilás na Figura 1.6b.

CAPÍTULO 2

ARTIGO 1

SEDIMENTATION PROCESSES IN THE NAVIGATION CHANNEL OF PATOS LAGOON ESTUARY, SOUTHERN BRAZIL

Aceito para publicação no periódico Regional Studies in Marine Science (ANEXO A).

2. SEDIMENTATION PROCESSES IN THE NAVIGATION CHANNEL OF PATOS LAGOON ESTUARY, SOUTHERN BRAZIL

Marine Jusiane Bastos da Silva[a,*], Iran Carlos Stalliviere Correa[a], José Antonio Scotti Fontoura[b] and Christian Garcia Serpa[b]

[a]Federal University of Rio Grande do Sul, Campus do Vale, Av. Bento Gonçalves, 7712 - Agronomia, Porto Alegre, Rio Grande do Sul, 91540-000; marinebastos@yahoo.com.br; iran.correa@ufrgs.br

[b]Federal University of Rio Grande, Campus Carreiros, Av. Itália, s/n - km 8 - Carreiros, Rio Grande, Rio Grande do Sul; scottifontoura@gmail.com; christianserpa@yahoo.com.br

*Corresponding author: marinebastos@yahoo.com.br

Abstract

The morphology of estuarine navigation channels varies in time and space. Siltation occurs in areas where flow conditions enable sediment trapping and it limits navigability in most cases, requiring periodic dredging. Identifying sedimentation patterns is fundamental to designing ports to reduce siltation. The Port of Rio Grande, located in the Patos Lagoon estuary, holds strategic significance and it is a key example for understanding the evolution of large estuarine access channels. We used 19 bathymetric surveys from April 2001 to February 2018 to generate Digital Elevation Models and evaluate the evolution in time of bed morphology in the Porto Novo basin and its access channel (located in Port of Rio Grande). Also, we considered hydrological data available from September 2005 to December 2011. Major siltation rates were observed in the northwestern portion of the basin and the convex margin of the access channel, whereas other locations exhibited stable conditions. Channel configuration and position were determinants to define spatial variations of sedimentation processes. Hydrological conditions, mainly when discharge exceeds 4,000 m^3/s over long periods, strongly controlled siltation magnitude in the Porto Novo basin and its access channel.

Keywords: port; estuary; siltation; navigation channel; sedimentation; Patos Lagoon.

2.1 Introduction

Evolution in time of estuarine navigation channels demonstrates the morphological response of interaction between different factors which control sediment dynamics, such as channel geometry, sediment characteristics, estuarine circulation, and human intervention. In the channel, sedimentation rates fluctuate due to spatial and temporal variations of these factors (e.g., Restrepo et al., 2020; Rahman and Ali, 2022). Also, harbors are located in a wide variety of water systems and different mechanisms play a role in each natural environment (Winterwerp, 2005).

Sediment is transported to harbor basins by the flow and it is deposited when the flow loses the ability to carry sediment (Winterwerp, 2005). Siltation occurs in areas where conditions enable sedimentation and it limits navigability in most cases, representing a risk to navigation and reducing accessibility to port infrastructure (Huguet et al., 2020). Periodic dredging is typically the strategy for the maintenance of ports and waterways because it removes trapped sediment and keeps the accessibility to the port (Kirichek et al., 2021), but it highly increases operational costs. Although dredging is fundamental to allow navigability, it is considered an economic and environmental issue.

Siltation-reduction strategies require a comprehensive understanding of the physical processes of deposition and must consider the natural system and its interaction with port geometry (Huguet et al., 2020). Identifying sedimentation patterns is fundamental to designing ports to reduce siltation. Analysis of *in situ* information as bathymetric data provides an improved understanding of morphological evolution and sedimentation processes (e.g. Cattani and Lamour, 2016; Zhu et al., 2019; Restrepo et al., 2020; Rahman and Ali, 2022) since bed morphology represents the consequence of the interaction of all parameters involved.

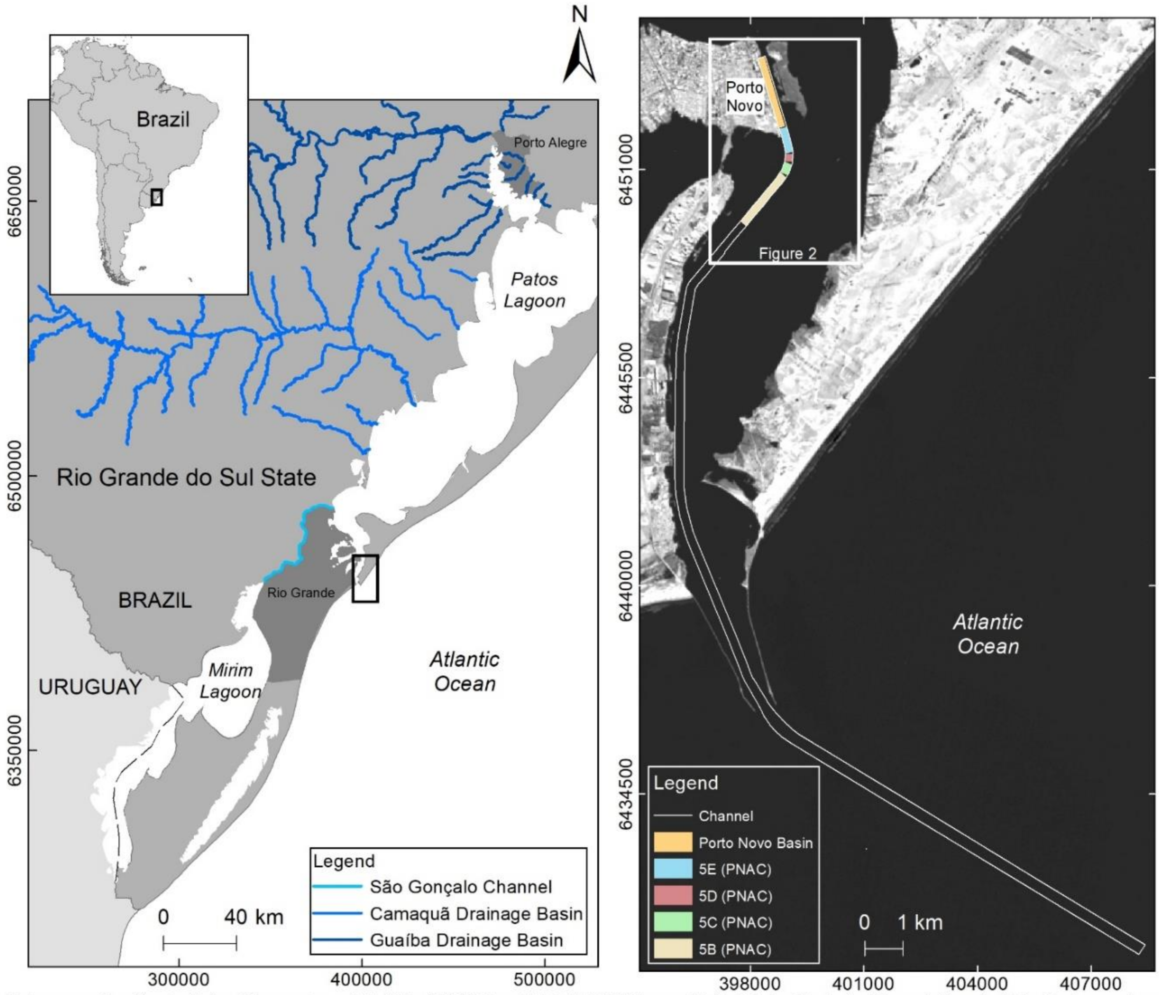
On the southern Brazilian coast, a major navigation channel links the estuary of Patos Lagoon – the largest choked coastal lagoon in the world (Kjerfve, 1986) – to the Atlantic Ocean. Intermittent sedimentation in the channel results in navigational limitations. This channel is unique access to the Port of Rio Grande and others located along Patos Lagoon. Dredging is required systematically and, besides its expressive cost, negative environmental impacts have been widely discussed by scientists (Calliari et al., 2020; Fernandes et al., 2021). An adequate investigation of channel sedimentation over time leads to the identification of sediment dynamics over time and space.

We selected the Porto Novo basin and its access channel, located in the Rio Grande Port (southernmost Brazil), for its strategic importance and because it is a key example for the understanding of the evolution of large access channels in estuarine systems. From January to May 2022, more than 4 million tons were handled in Porto Novo, representing 27.44% of which were handled in Port of Rio Grande during this period (Portos RS, 2022a). We used 19 bathymetric surveys from April 2001 to February 2018 to analyze the bed evolution of the selected area. Hydrological data (mean monthly discharge of Patos Lagoon), from September 2005 to December 2011, was also considered to support the analysis of the morphodynamic variations over time.

We identified areas where deposition is predominant over time, associated with the position and geometry of the channel. Hydrodynamic conditions, mainly the discharge, are a key factor to control siltation. Also, natural morphology before human intervention influences sedimentation patterns currently observed. The analysis of in-situ data from 17 years for a 919,600 m² area provided a significant contribution to understanding how the bed morphology of estuarine navigation channels varies in time and space. Despite the economic and social importance of this estuary, there are no previous studies that evaluated the morphological evolution of Patos Lagoon channels considering *in situ* data for this time interval.

2.2 Study Area

Patos and Mirim Lagoons drain a 199,000 km² basin and are linked by the São Gonçalo channel (Hartmann and Schettini, 1991), forming the Patos-Mirim lagoon system (Figure 2.1). The main tributaries are the Guaiba and Camaquã rivers (Möller et al., 2001). The Patos Lagoon comprises a surface area of 10,227 km² with a mean depth of 5 m. The 180 km length of the main axis extends in the NE-SW direction (Calliari et al., 2008). In the estuarine area, a unique narrow channel links the Patos Lagoon to the Atlantic Ocean. In this inlet, bordered by two 4 km long jetties (Calliari et al., 2020), the channel has been dredged to attain a depth of up to 18 m since 2018.



Data source: Brazilian Institute of Geography and Statistics (IBGE); LandSat 8 OLI_TIRS Image (United States Geological Survey); Secretariat for Environment and Infrastructure of Rio Grande do Sul (Drainage basins data). Coordinate system: WGS 1984. Projection: UTM, 22 S.

Figure 2.1: Location of the study area. The study area comprises the Porto Novo Basin and 5E, 5D, 5C, and 5B areas of the Porto Novo Access Channel (PNAC). “Figure 2” is related to the Figure 2.2.

The Port of Rio Grande, one of the largest in Brazil, is located on the western margin of the Patos Lagoon estuary. More than 45 million tons were handled in 2021, the largest mark in the last 12 years (Portos RS, 2022b). The Port of Rio Grande is divided into four areas from the southern to the northern portion of the channel: External Channel (18 m depth), Internal Channel (16 m depth), Superporto (16 m depth), and Porto Novo (10.5 m depth). Besides the Rio Grande Port access channel, the Porto Novo basin and its access channel are sites with bulkier dredging currently (Calliari et al., 2020).

Due to a political decision to establish the port in the vicinity of Rio Grande town in the early 1900s, the Porto Novo basin was opened by dredging where Coroa do Ladino was originally located (Figure 2.2), a shallow underwater area (Calliari, 1980). Currently, trailing suction hopper dredgers (TSHD) are used to dredge the region, and backhoe or clamshell dredges are used where TSHD maneuverability becomes impaired (in the area next to Porto Novo quay, for example). The frequency of dredging is not fixed, depending on the magnitude of siltation in the period, the availability of economic resources, and permits from government authorities.

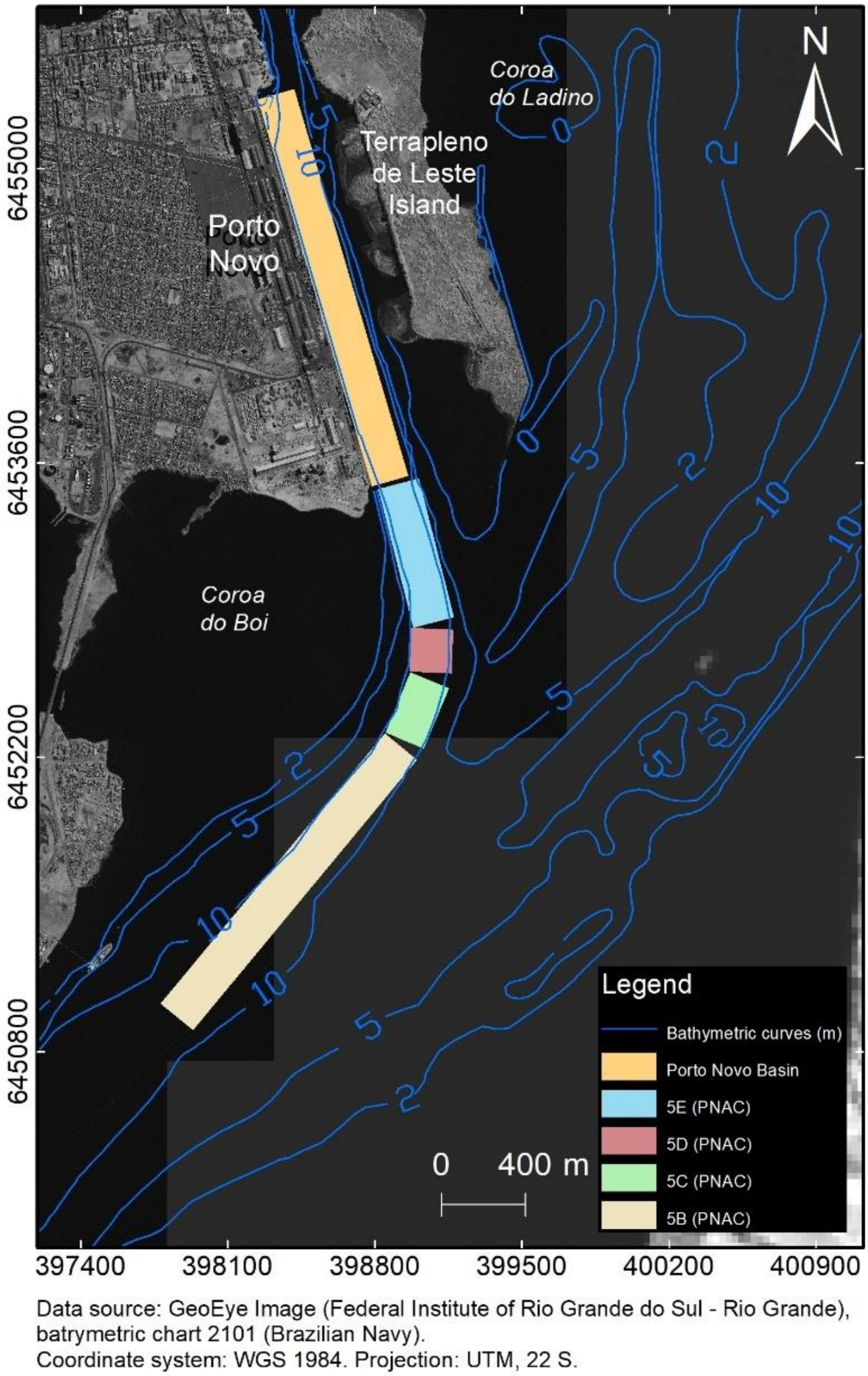


Figure 2.2: The study area – Porto Novo Basin and 5E, 5D, 5C, and 5B areas of Porto Novo Access Channel (PNAC).

Wind forces and freshwater discharge are the most important agents controlling estuarine hydrodynamics in Patos Lagoon (Hartmann and Schettini, 1991; Möller and Castaing, 1999). The region presents a microtidal regime, with a mean tidal amplitude of 0.47 m, and tides are mixed, mainly of the diurnal type (Fernandes et al., 2005). The choked morphology reduces the tidal energy by 80% due to friction (Möller and Fernandes, 2010).

The most frequent winds are from NE with a mean velocity of 5 m/s, followed by winds from SW with a mean velocity of 8 m/s, which are associated with the passage of frontal systems (Klein, 1998). These predominant wind directions coincide with the lagoon's main axis. The wind action in the region of Patos Lagoon is associated with the differences in the water level inside the lagoon and the coastal area, caused by local (wind acting in the lagoon axis) and non-local (Ekman transport in the coastal area) effects (Möller et al., 2001; Fernandes et al., 2002). During NE (SW) wind events, seaward (landward) flows are observed (Möller et al., 2001; Fernandes et al., 2002).

The average annual freshwater flow in the estuary is around 4,000 m^3/s, and peaks up to 10,000 m^3/s during El Niño events (Seeliger, 2001), a phenomenon that increases rainfall in the drainage basin (southern Brazil). Rivers comprised by the Patos-Mirim lagoon system drainage basin normally present high discharge in late austral winter and early spring, and low to moderate discharge in austral summer and autumn (Calliari et al., 2008). António et al. (2020) considered that freshwater inflow is a major controlling force in the dynamics of Patos Lagoon. Discharge higher than 3,000 m^3/s blocks saline water intrusion into the estuary (Möller et al., 1991; Calliari et al., 2008; Möller and Fernandes, 2010).

Although coastal lagoons are generally considered well-mixed types of estuaries, stratification is a dominant feature in Patos Lagoon, due to its hydrodynamic and morphological characteristics (Möller and Castaing, 1999). Large freshwater discharge, predominant winds from NE, and the funneling and deep inlet increase the effect of freshwater flow, contributing to a two-layer vertical profile (Möller and Castaing, 1999). According to Barros et al. (2014), freshwater discharge intensity defines the vertical stratification of the estuary.

Hartmann and Schettini (1991) identified the four estuarine circulation models described by Cameron and Pritchard (1963) and Pritchard (1967) in the Patos Lagoon estuary. The authors also observed that estuarine circulation conditions can change quickly due to meteorological variations in the inlet area. Low discharge (austral summer and autumn), SE, and SW winds force the intrusion of seawater towards the inlet, whereas NE winds associated with high discharge reduce estuarine salinity (Fernandes et al., 2005). Data analyzed by Möller and Castaing (1999) indicated that only strong winds can force salt water into the lagoon when river flow exceeds 4,500 m^3/s because the intrusion is rapidly flushed out of the channel.

According to Calliari et al. (2008), the estuarine area receives a considerable fluvial input of fine sediments (silt and clay) due to high rainfall in the drainage basin. Important sources of sediments are also from the hydrodynamic erosion of estuarine margins, lagoon terraces, marshes, and benthic estuarine and flora (Calliari et al., 2008). The distribution of bottom types in the estuary is related to depth and hydrodynamic energy levels and thus silty clay is predominant in deep channels and shallow protected environments (Calliari, 1997). Sandy bottoms predominate in shallow marginal areas but are also found in channels with high hydrodynamic energy (Calliari et al., 2008). In the Porto Novo basin silty clay is predominant, but mixed sediment patterns (sand, clay, silt) are observed in the Porto Novo access channel (Calliari, 1997).

2.3 Materials and Methods

The analysis of channel bed topography over time was based on geo-referenced bathymetric datasets provided by Portos RS (Rio Grande Port Authority). All bathymetric surveys were standardized to Universal Transverse Mercator (UTM), WGS 84, 22 S. Elevation values (m) were relative to the local lowest tide level defined by Diretoria de Hidrografia e Navegação, used in the form provided.

Bathymetric surveys comprised the following years and months: 2001 (April, May); 2002 (March); 2004 (April, July); 2005 (March); 2006 (January, June); 2007 (May, June, October); 2008 (March); 2009 (January, May); 2011 (February, December), 2012 (March); 2015 (November) and 2018 (February). Bathymetric surveys from April 2001 and May 2001 did not include the basin area; bathymetric surveys from May 2001, March 2002, and April 2004 included only the basin.

The bathymetric surface comparisons require the development of tridimensional models that can be estimated from rectangular grids or triangular irregular networks. For each bathymetric survey and each rectangular area, we generated digital elevation models (DEM). DEMs were estimated from rectangular grids, using the Kriging method at Surfer software. Because these bathymetric surveys do not present a regular point spacing, DEMs were constructed with cell sizes of 10 m.

The Porto Novo basin and its access channel were divided into five rectangular areas for this study: basin, 5E, 5D, 5C, and 5B (Figure 2.2). Dimensions and vertices coordinates are presented in Table 2.1. Rectangles were divided considering the following information:

(i) The Port Authority divides the Porto Novo area into an area called Porto Novo basin (next to the quay) and an access channel (Figure 2.2). Both basin and access channel are dredged to attain a 10.5 m depth;

(ii) Porto Novo basin was represented by a single rectangle (basin), and the Porto Novo access channel was divided into 4 rectangles (5E, 5D, 5C, and 5B) (Figure 2.2);

(iii) The division of Porto Novo access channels into rectangles considered the channel orientation.

Table 2.1: Characteristics of rectangular areas: Porto Novo basin and its access channel (5E, 5D, 5C, 5B), UTM 22 S. *For the period between November 2015 and February 2018, it was considered 170 m in width, because Porto Novo quay was expanded 10 m towards the basin.

	Basin	5E	5D	5C	5B
Width (m)	180*	200	200	200	200
Length (m)	1920	680	210	310	1,670
Area (m²)	345,600	136,000	42,000	62,000	334,000
Vertex 1					
E (m)	398786.3644	398981.6885	398963.9005	398849.047	397779.1387
N (m)	6453487.318	6452816.6073	6452607.0415	6452317.2177	6451029.0702
Vertex 2					
E (m)	398959.0058	399175.5278	399163.6761	399033.8592	397933.0015
N (m)	6453538.2585	6452865.8651	6452597.5698	6452240.7687	64500901.296
Vertex 3					
E (m)	398415.6407	399008.0513	399173.6214	399152.3352	398999.9159
N (m)	6455379.7672	6453524.9187	6452807.3342	6452527.2275	6452186.0503
Vertex 4					
E (m)	398242.9992	398814.212	398973.8458	398967.543	398846.0531
N (m)	6455328.8267	6453475.6608	6452816.8059	6452603.6766	6452313.8245
θ (°)	16.43949666°	14.25802347	2.71445695	22.42783148	39.70767686

Considering that the Kriging method creates rectangular grids, with horizontal lines and vertical columns, we rotate each rectangular area and its bathymetric dataset around a fixed vertex using angle θ (Figure 2.3a). We established the dataset so the length is north (Figure 2.3b) and we generated DEM considering data with this orientation (Figure 2.3c). This procedure of rotating the dataset guaranteed that DEMs presented columns that were parallel to the main axis of the channel and lines that were perpendicular to this axis. We also guaranteed that no grid nodes were created outside the limits of each rectangle. After applying the Kriging method, we rotated each DEM to its original position (Figure 2.3d). The division of the study area in rectangles allowed for standardizing the areas for comparisons and obtaining a better performance to create rectangular grids, through the Kriging method.

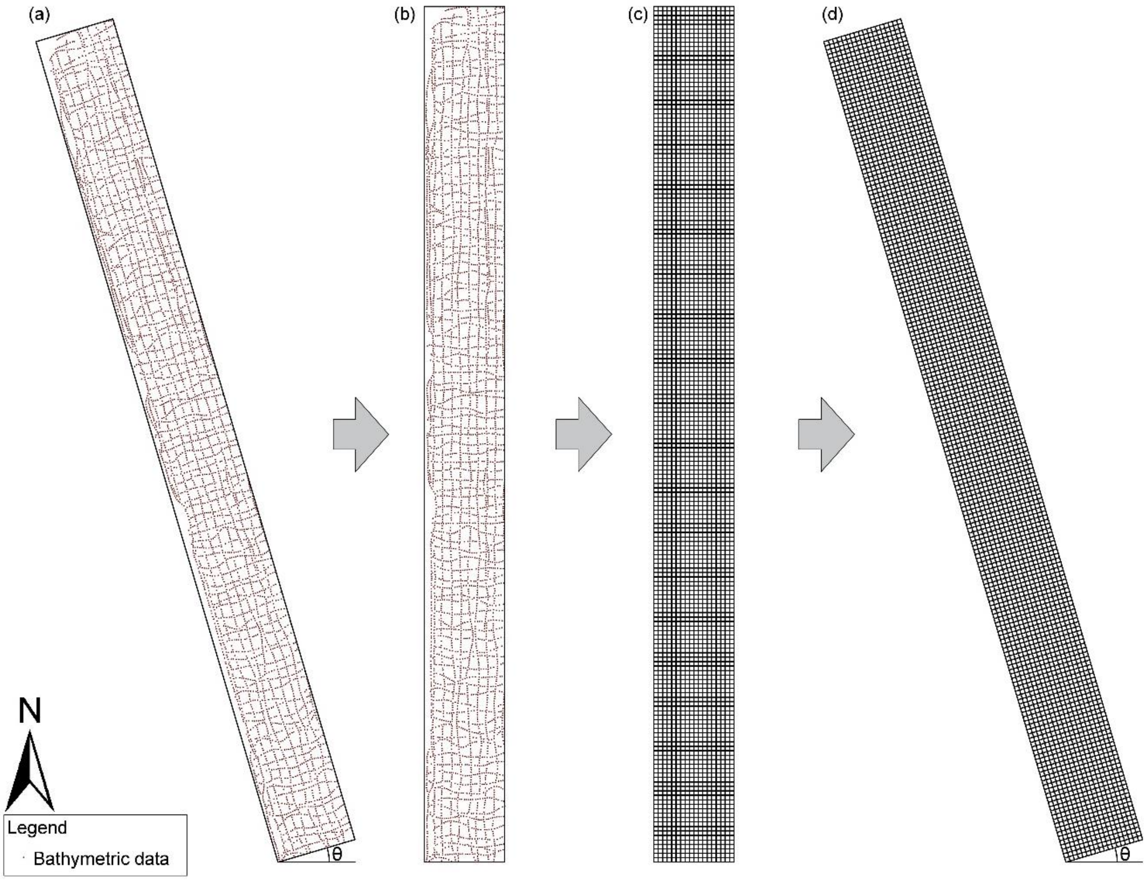


Figure 2.3: The procedure applied to each rectangular area and its bathymetric dataset. (a) The dataset in its original configuration; (b) Rotation so the length is north; (c) MDE generation using the Kriging method; (d) Rotation of MDE to the original position of the rectangle, with lines parallel to the main axis and columns perpendicular to the main axis.

Data were also divided into five periods between dredging activities (called inter-dredging periods), to comprise only volume variations due to natural processes. According to data from Port Authority, we identified the following dredging periods on the Porto Novo basin and its access channel between 2000 and 2018: July to December 2000, April to May 2004, July to October 2006, October 2009 to February 2010, July to October 2012, and December 2013 to January 2014.

Time intervals between two DEMs were calculated considering the last day of bathymetric survey measurements. For example, bathymetric survey measurements from May 2007 were finished on 17 May 2007 and bathymetric survey measurements from May 2009 were finished on 02 May 2009. In this case, there is a 716 days interval, which represents 23.87 months (considering 30 days as 1 month).

Volumetric differences were based on a geometric comparison between two DEMs, one as an upper surface and another as a lower surface. The lower surface (considered as a reference) was the older DEM at the analyzed time interval. We compared DEMs from successive bathymetric surveys and also the first and the last DEM of each inter-dredging period. Volumes above the reference were considered deposition and volumes below the reference were considered erosion.

Maps were constructed by comparing values of the same grid points between two DEMs. For maps, we considered that changes in the interval between – 0.25 m and + 0.25 m are not significant (stable condition). These areas were represented in white. This threshold was defined considering the total vertical uncertainty (TVU) admitted for areas where under-keel clearance is critical, according to the International Hydrographic Organization (2020). Considering the formulation proposed by International Hydrographic Organization (2020), TVU is approximately ±0.25 m for a 10.5 m depth. However, it is an estimated value.

We also considered the mean monthly discharge data of the Patos Lagoon inlet (32.14° S; 52.10° W) in the analysis of the morphodynamic evolution. These data were obtained from the National Water and Sanitation Agency of Brazil (ANA, www.snirh.gov.br/hidroweb/), for the period between September 2005 and December 2011. Data were used as provided and considering that positive values indicated flood flow (landward) and negative values indicated ebb flow (seaward) in the inlet. Data from the following periods were not available: before September 2005, from August 2009 to April 2010, May 2011, and after December 2011.

2.4 Results

Deposited volumes for each sector are presented in Table 2.2. For DEM comparisons older DEM in the interval was taken as a reference and volumes above this reference were considered deposition.

Table 2.2: Deposited volumes in the Porto Novo basin and its access channel (5E, 5D, 5C. 5B). *Area: 326,400 m².

Bathymetric surveys	Interval (month)	Deposition (m³)				
		Basin	5E	5D	5C	5B
Inter-dredging period 1						
April 2001/May 2001	0.57		222	17	115	973
May 2001/March 2002	9.93	120,543				
March 2002/April 2004	25.20	81,980				
May 2001/April 2004	35.13	179,047				
Inter-dredging period 2						
July 2004/March 2005	8.20	82,963	128,403	3,074	989	4,053
March 2005/January 2006	10.13	78,108	38,465	5,409	7,327	71,951
January 2006/June 2006	4.73	135,235	70,304	17,697	8,985	58,179
July 2004/June 2006	23.07	233,065	190,628	18,631	7,750	58,992
Inter-dredging period 3						
May 2007/June 2007	0.87	5,921	1,395	646	243	476
June 2007/October 2007	4.43	2,352	965	297	257	67
October 2007/March 2008	4.67	273,603	181,659	26,584	26,651	101,830
March 2008/January 2009	10.10	74,712	79,326	11,129	5,397	25,037
January 2009/May 2009	3.80	126,424	47,592	20,409	17,341	20,674
May 2007/May 2009	23.87	112,386	46,863	12,373	3,544	26,482
Inter-dredging period 4						
February 2011/December 2011	10.07	85,582	51,388	6,483	7,689	6,582
December 2011/March 2012	2.83	32,914	40,454	7,587	5,489	40,766
February 2011/March 2012	12.90	102,035	88,214	12,475	11,267	34,878
Inter-dredging period 5						
November 2015/February 2018	27.80	99,375*	80,931	22,729	32,831	126,152
Planar area of the rectangle (m²)		345,600	136,000	42,000	62,000	334,000

Eroded volumes for each sector are shown in Table 2.3. The same time intervals and data in Table 2.2 are presented. Volumes below the reference (older DEM in the considered period) were considered erosion. Net volumes were estimated based on the sum of deposition volumes (+) and erosion volumes (-) for each period.

Table 2.3: Eroded volumes in the Porto Novo basin and its access channel (5E, 5D, 5C. 5B). *Area: 326,400 m².

Bathymetric surveys	Interval (month)	Erosion (m³)				
		Basin	5E	5D	5C	5B
Inter-dredging period 1						
April 2001/May 2001	0.57		-163,300	-38,836	-42,223	-49,236
May 2001/March 2002	9.93	-46,697				
March 2002/April 2004	25.20	-21,247				
May 2001/April 2004	35.13	-44,468				
Inter-dredging period 2						
July 2004/March 2005	8.20	-75,013	-9,550	-8,178	-15,471	-80,708
March 2005/January 2006	10.13	-14,032	-37,796	-140	-284	-409
January 2006/June 2006	4.73	-5,301	-603	-3	-155	-754
July 2004/June 2006	23.07	-31,104	-1,404	-771	-6,360	-6,679
Inter-dredging period 3						
May 2007/June 2007	0.87	-121,742	-21,738	-5,993	-7,392	-38,867
June 2007/October 2007	4.43	-211,112	-235,412	-40,018	-35,900	-67,158
October 2007/March 2008	4.67	-15,750	0	-46	-11	-56
March 2008/January 2009	10.10	-68,096	-10,119	-122	-3,903	-24,202
January 2009/May 2009	3.80	-23,103	-2,492	-516	-1,577	-20,186
May 2007/May 2009	23.87	-69,176	-5,687	-2	-2,437	-28,867
Inter-dredging period 4						
February 2011/December 2011	10.07	-34,804	-9,293	-1,931	-2,616	-18,212
December 2011/March 2012	2.83	-26,005	-872	0	-281	-1,508
February 2011/March 2012	12.90	-44,348	-6,537	-335	-985	-7,251
Inter-dredging period 5						
November 2015/February 2018	27.80	-46.073*	-676	-48	-3	-235
Planar area of the rectangle (m²)		345,600	136,000	42,000	62,000	334,000

2.4.1 Inter-dredging period 1

The inter-dredging period 1 comprises DEM comparisons from April 2001 to April 2004 (Figure 2.4). From April 2001 to May 2001 (0.57 month), 1,327 m³ of sediments were deposited in the whole access channel (5E, 5D, 5C, and 5B) (Table 2.2) and 293,595 m³ of sediments were eroded from this area (Table 2.3). More than 55% of the eroded sediment was removed from the 5E area (~136,000 m²), followed by 5B, 5C, and 5D (Table 2.3). Maps indicated that volume variations on 5B induced depth variations from +0.25 to -0.25 m, which is considered a stability condition in this study (Figure 2.4d). In the 5E, 5D, and 5C areas, we observed depth variations up to -4.9 m in the western margin of the access channel (convex form) and -1.9 m in the eastern margin (Figure 2.4d).

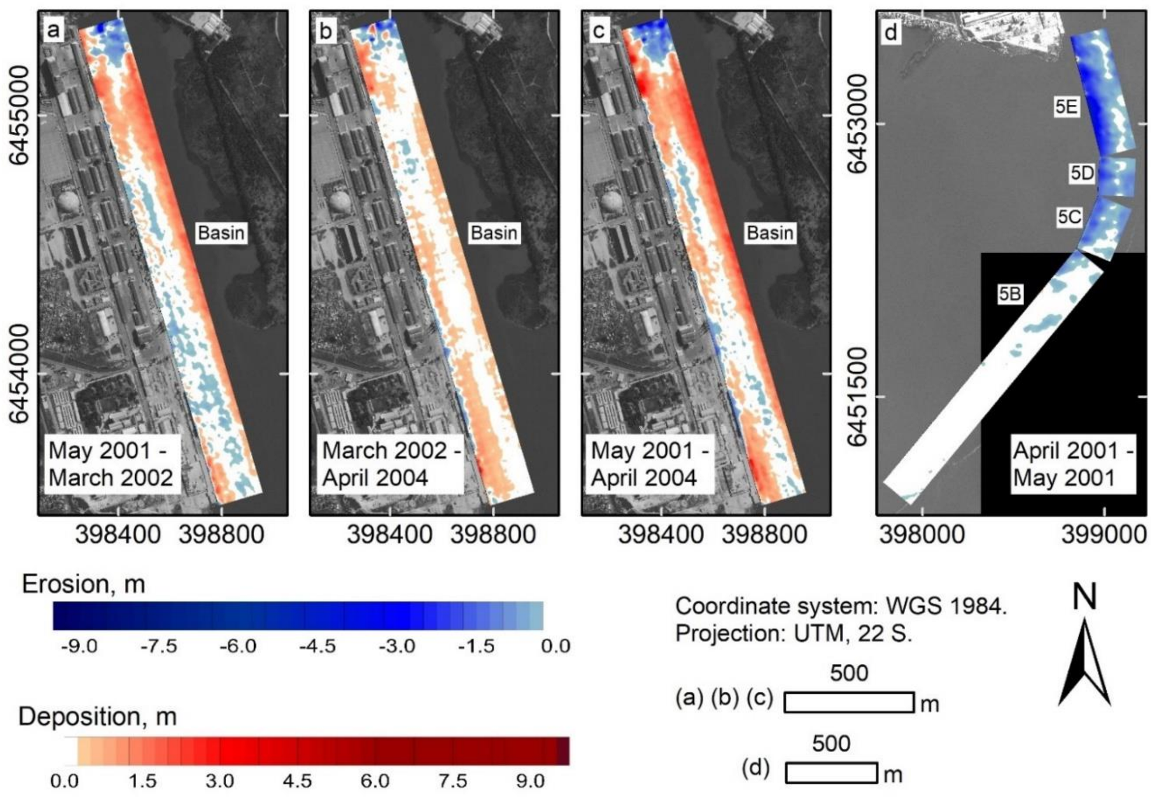


Figure 2.4: Bed evolution during inter-dredging period 1. Values between ±0.25 m were considered stable condition (white color).

From May 2001 to April 2004 (Figure 2.4a,b,c), 179,047 m³ of sediments entered the basin area (Table 2.2) and 44,468 m³ were eroded (Table 2.3), representing a net volume of +134,579 m³ in 35.13 months. From May 2001 to March 2002 (9.93 months), the net volume was +73,846 m³, while a net volume of +60,733 m³ was estimated between March 2002 and April 2004 (~25.20 months) (Table 2.2, Table 2.3). Evolution in time of basin (Figure 2.4a,b,c) indicated stable condition in the central axis of the basin, and deposition occurred, generally, in marginal positions and in the northwestern portion of this area, where depth variations up to +3.2 m were observed in some points. In the western margin, variations up to +2.5 m were found (Figure 2.4a,c). Also, on the northwesternmost of the basin, there was a location where significant erosion rates were observed, and variations in depth greater than -3.9 m were found (Figure 2.4a,b,c). An access channel to the basin with ~130 m in width is located on the northwesternmost region of the basin (Figure 2.2).

2.4.2 Inter-dredging period 2

The inter-dredging period 2 comprises DEM comparisons from July 2004 to June 2006 (Figure 2.5). In the time interval between July 2004 and March 2005 (Figure 2.5a), the net volume was +7,950 m^3 in the basin, +118,853 m^3 in the 5E area, -5,104 m^3 in the 5D area, -14,482 m^3 in the 5C area and -76,655 m^3 in the 5B area (Table 2.2, Table 2.3). The analysis of the bed channel during these 8.2 months demonstrated a slight erosion in the 5D, 5C, and 5B areas (Figure 2.5a). The deposited volume mainly occurred in the 5E rectangle, in the northwestern portion of the basin, and in the western and northern borders of the access channel.

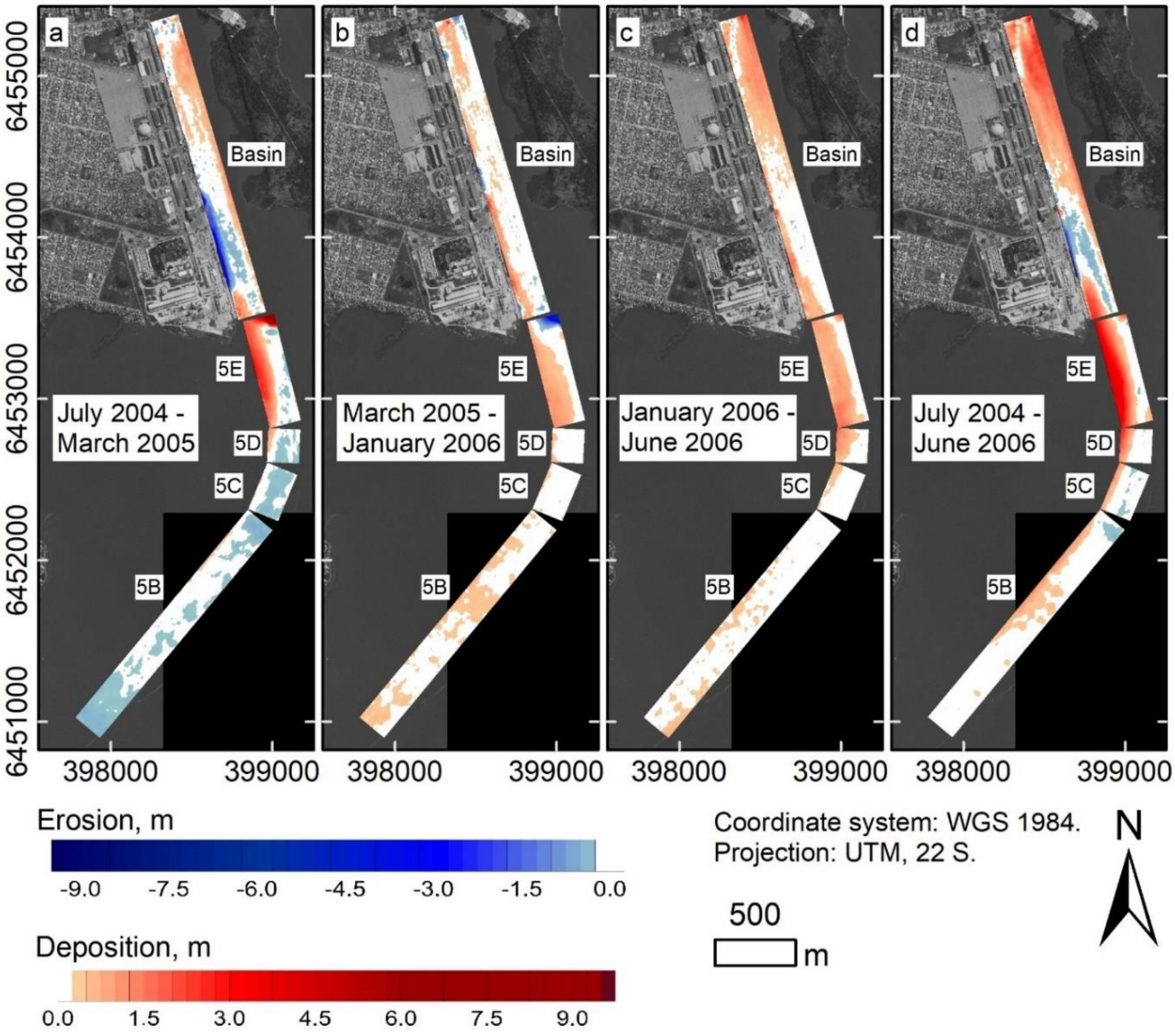


Figure 2.5: Bed evolution during inter-dredging period 2. Values between ±0.25 m were considered stable condition (white color).

Between March 2005 and January 2006 (Figure 2.5b), small deposition rates were observed in the area and the net volume in the whole area was +148,599 m^3 (Table 2.2, Table 2.3). From January 2006 to June 2006 (Figure 2.5c), net volume reached +283,584 m^3 in the whole area (Table 2.2, Table 2.3), and 70.40% of this value corresponded to the basin and the 5E sectors.

From July 2004 to June 2006 (Figure 2.5d), depths in the convex margin of the access channel (western margin of 5E, 5D, and 5C) and the northwestern portion of the basin gradually decreased due to a large volume of sediments that entered the area and the net volume attained +462,748 m^3 (Table 2.2, Table 2.3). From the total net volume during these 23.07 months, 43.6% was trapped in the basin (201,961 m^3) and 40.9% in the 5E rectangle (189,224 m^3) (both occupying a 481,600 m^2 area). Only 15.5% were trapped in 5D, 5C, and 5B areas (438,000 m^2).

2.4.3 Inter-dredging period 3

The inter-dredging period 3 comprises DEM comparisons from May 2007 to May 2009 (Figure 2.6). From May 2007 to June 2007 (0.87 month), a total deposition of 8,681 m^3 occurred in the study area (Table 2.2), and natural erosion of 195,732 m^3 of sediments (Table 2.3). We observed that 62.2% of erosion occurred in the basin area, 19.9% of sediments were removed from the 5B area and 11.1% was eroded from the 5E area. The basin demonstrated depth variations from -0.2 m to -0.6 m in most points and deposition up to 1.0 m in the northwesternmost point (Figure 2.6a).

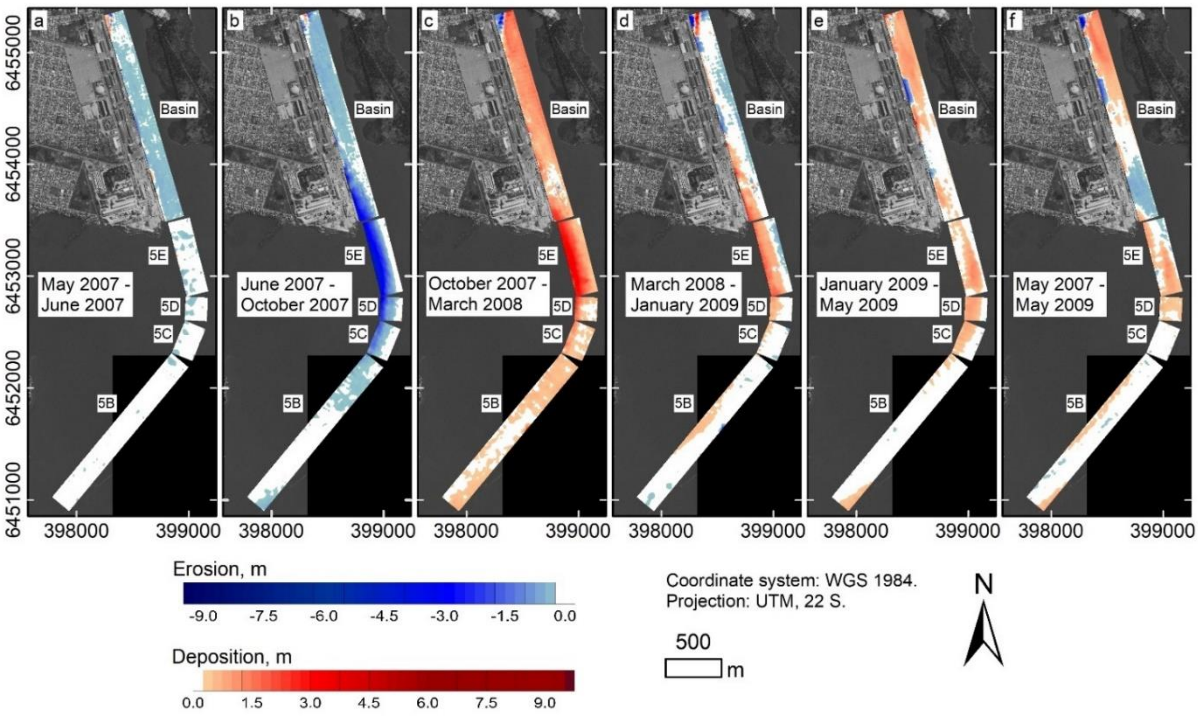


Figure 2.6: Bed evolution during inter-dredging period 3. Values between ±0.25 m were considered stable condition (white color).

The predominant erosive process continued between June 2007 and October 2007 (~4.43 months), when only 3,938 m³ were deposited in the whole area (Table 2.2). However, 589,600 m³ were naturally eroded during this period (Table 2.3), resulting in a net volume of -585,662 m³. No dredging activity is registered at this period. This time interval represented the largest erosional event at nearly 17 years. Analyzing bed evolution during these 4.43 months (Figure 2.6b), we detected that the convex border in the access channel was strongly eroded. In the 5E area, DEMs comparisons of depth variations larger than -5.6 m were found. The concave margin of the access channel and the southeastern portion of the basin exhibited a stable pattern. Also, no large depth variations were noticed in the 5B sector.

In the following 4.67 months (from October 2007 to March 2008), a strongly depositional process was noticed, when 610,327 m³ entered the considered area (Table 2.2) and only 15,863 m³ of sediments were removed (Table 2.3), representing a net volume of +594,464 m³. The largest rates of sedimentation were found in the convex margin of the 5E area, reaching more than +3.0 m at some points (Figure 2.6c).

Between March 2008 and January 2009 (~10.10 months), net volumes were: +6,616 m³ in the basin, +69,207 m³ in the 5E area, +11,007 m³ in the 5D area, +1,494 m³ in the 5C area and +835 m³ in the 5B area. There was a continued sedimentation process in the convex margin of the channel (Figure 2.6d), that had been detected since October 2007. Nevertheless, in the concave margin of the access channel, in most parts of the basin, and the 5B rectangle a stable condition is observed.

From January 2009 to May 2009 (Figure 2.6e), a stable condition is observed in the southeastern portion of the basin and again in the 5B area. The net volume was +184,566 m^3 and 80.4% of sediments were trapped in the basin and the 5E sectors. Siltation was predominant in the northwestern portion of the basin and it also increased toward the central axis of the 5E, 5D, and 5C areas in the access channel.

Over 2 years (May 2007 – May 2009), the net volume was +43,210 m^3 in the basin (345,600 m^2), +41,176 m^3 in the 5E area (136,000 m^2), +12,371 m^3 in the 5D area (42,000 m^2), +1,107 m^3 in the 5C area (62,000 m^2) and -2,385 m^3 in the 5B area (334,000 m^2), according to Table 2.2 and Table 2.3. Most sediments were trapped in the northwestern portion of the basin and the 5E and 5D areas (Figure 2.6f).

2.4.4 Inter-dredging periods 4 and 5

The inter-dredging periods 4 and 5 comprise DEM comparisons from February 2011 to March 2012 and from November 2015 to February 2018 (Figure 2.7). From February 2011 to December 2011, the net volume was +50,778 m^3 in the basin, +42,095 m^3 in the 5E area, +4,552 m^3 in the 5D area, +5,073 m^3 in the 5C area and -11,630 m^3 in the 5B area (Table 2.2, Table 2.3). Sediments were mostly trapped in the northwestern portion of the basin and the convex margin of the channel, mainly in 5E rectangle (Figure 2.7a). During the following 2.83 months (December 2011 – March 2012), a small deposition occurred and the same environmental process was observed (Figure 2.7b).

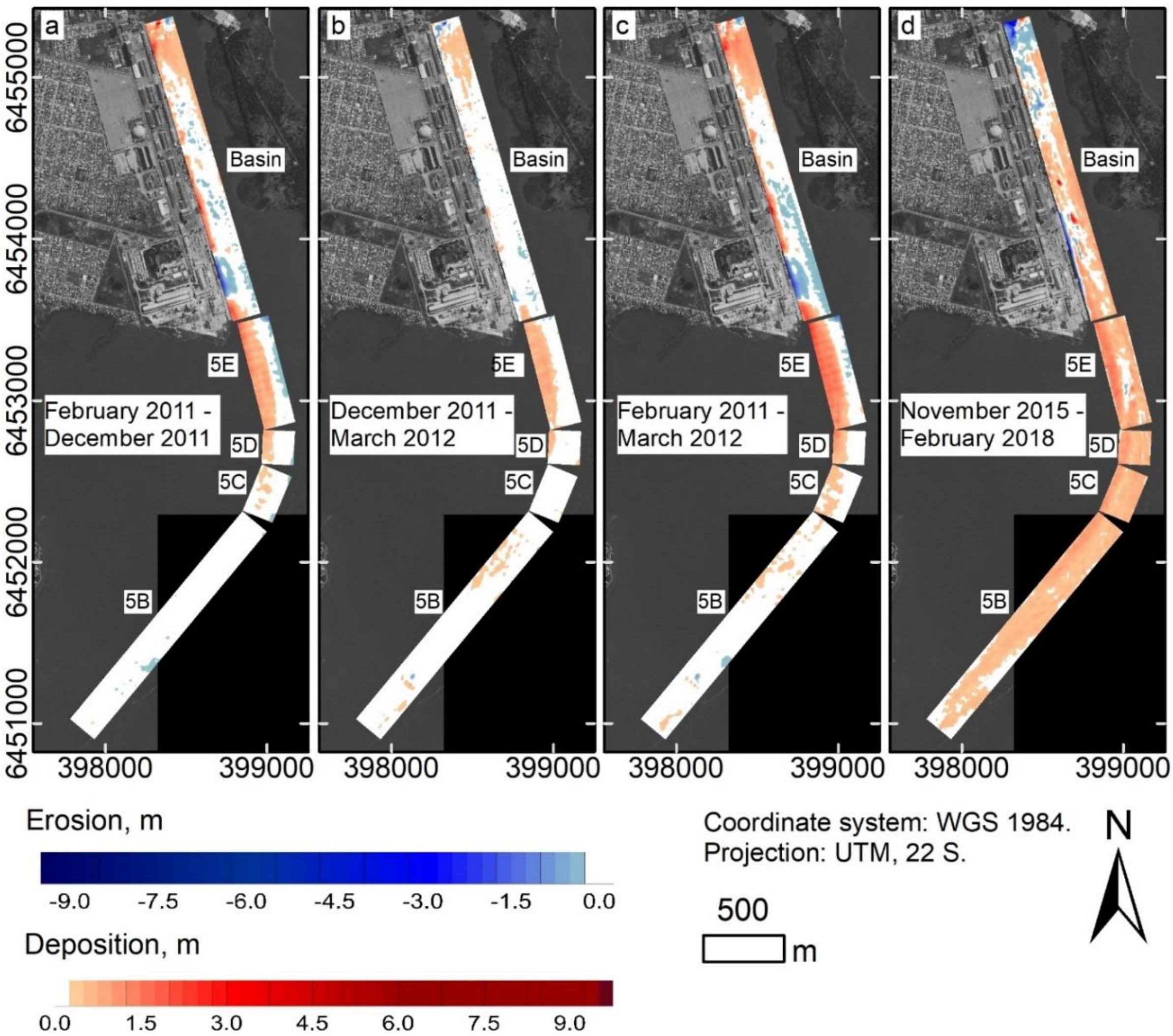


Figure 2.7: Bed evolution during inter-dredging periods 4 and 5. Values between ±0.25 m were considered stable condition (white color).

From February 2011 to March 2012, covering nearly 13 months, two locations were characterized for trapping more sediments: the northwestern portion of the basin and the convex margin in the access channel (Figure 2.7c). In the 5B rectangle, we considered that the deposition of 34,878 m³ in this area made depths vary up to 0.25 m, representing a stable area in this period. Net volumes were +57,687 m³ in the basin, +81,677 m³ in the 5E sector, +12,140 m³ in the 5D sector, +10,282 m³ in the 5C sector, and +27,627 m³ in the 5B sector (Table 2.2, Table 2.3). Therefore, the basin and the 5E areas answered for 73.6% of positive net volumes that were observed in the Porto Novo basin and access channel.

DEM comparisons of November 2015 and February 2018 corresponded to inter-dredging period 5 (Figure 2.7d). The net volume was +314,983 m³ in the study area

(Table 2.2, Table 2.3). A total of 42.4% of the positive net volume was comprised of the basin and the 5E sector at this period.

2.4.5 Inter-dredging periods *comparison*

The comparison between the first and the last DEM of each inter-dredging period was analyzed. We identified a net volume of +462,748 m^3 from July 2004 to June 2006 and 84.5% of this value corresponds to the basin and the 5E areas (Table 2.2, Table 2.3). Between May 2007 and May 2009, 86.3% of the whole positive net volume observed (+97,864 m^3, not considering the negative net volume from the 5E area) is related to the basin and the 5E rectangle (Table 2.2, Table 2.3). From February 2011 to March 2012, the net volume was +189,413 m^3 and 73.6% was related to the same area (Table 2.2, Table 2.3). In the period between November 2015 and February 2018, 42.4% of the total net volume (+314,983 m^3) corresponded to the basin and the 5E areas (Table 2.2, Table 2.3).

The analysis of net sedimentation rates in each inter-dredging period for each rectangular area (Figure 2.8) demonstrated that the most erosional behaviors occurred from April 2001 to May 2001 in the Porto Novo access channel (Figure 2.8a), from May 2007 to June 2007 (Figure 2.8c) and from June 2007 to October 2007 (Figure 2.8c) in the whole area. Net sedimentation rates were obtained by dividing net volumes (m^3) by time interval (month) and by the planar rectangular area (m^2), using data from Table 2.2 and Table 2.3. The comparison of net sedimentation rates between the first and the last DEM of each inter-dredging period (Figure 2.8f) indicated that positive net volumes were dominant in the environment.

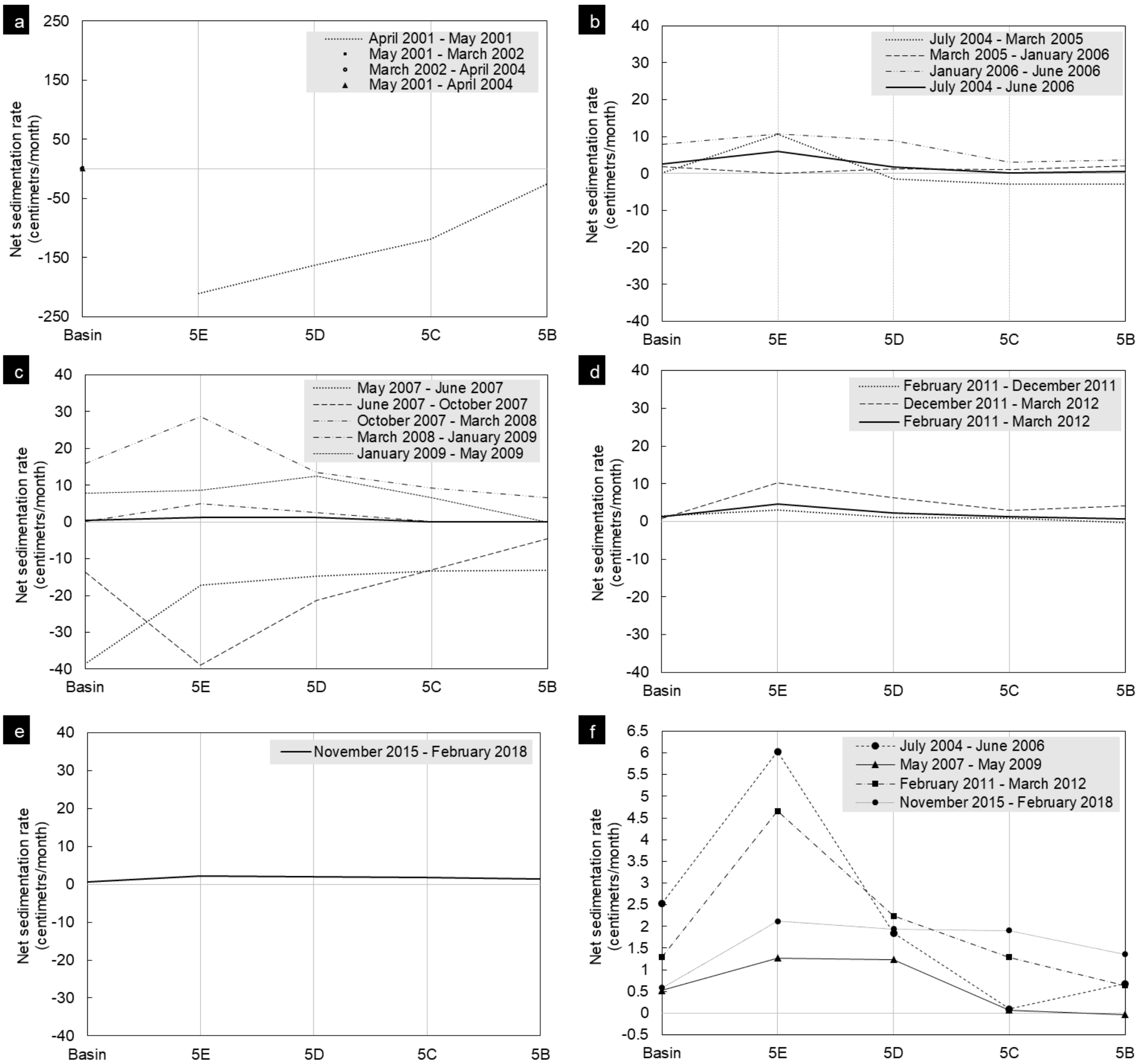


Figure 2.8: Analysis of net sedimentation rates in the (a) inter-dredging period 1; (b) inter-dredging period 2; (c) inter-dredging period 3; (d) inter-dredging period 4; (e) inter-dredging period 5; (f) comparison of net sedimentation rates between the first DEM and the last DEM of inter-dredging periods 2, 3, 4 and 5, which covered the entire area (the basin and the access channel).

2.4.6 *Hydrological data*

The analysis of hydrological data aimed to support the comprehension of sedimentation and erosion patterns. Mean monthly discharge data were obtained from September 2005 to December 2011 (Figure 2.9). Data before September 2005 and after December 2011 were not available.

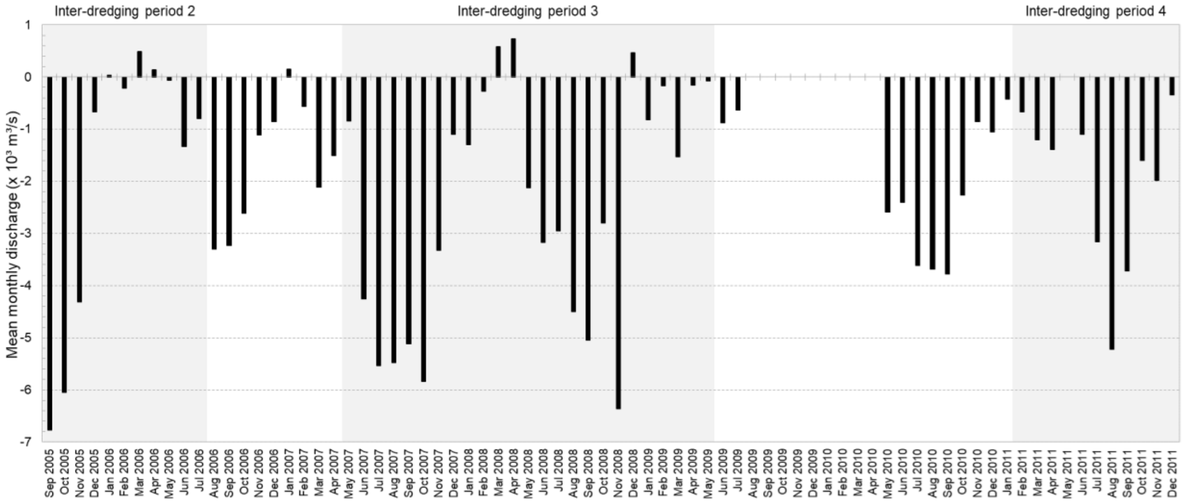


Figure 2.9: Mean monthly discharge in Patos Lagoon (ANA). (+) Flood flow and (-) Ebb flow. Discharge data from August 2009 to April 2010 and May 2011 were not available.

The ebb flow was predominant in the following periods: September-December 2005, May-December 2006, February 2007-February 2008, May-November 2008, January 2009-July 2009, May 2010-April 2011, and June 2011-December 2011 (Figure 2.9).

From January 2006 to June 2006, the mean monthly discharge oscillated slightly between flood and ebb flow. For comparison, a different pattern was observed from January 2009 to May 2009, when the ebb flow was dominant.

In the period between February 2007 and February 2008, the ebb flow was predominant in the Patos Lagoon inlet. The average monthly discharge increased 405.7% between May 2007 (-841 m^3/s) and June 2007 (-4,253 m^3/s). The average monthly discharge reached more than -5,000 m^3/s in July 2007 and this magnitude remained until October 2007, when it attained -5,830 m^3/s.

From May 2008 to November 2008, an intense ebb flow was also observed, but it varied in magnitude. In August and September 2008, mean monthly discharge attained an order of -5,000 m^3/s and reached -6,357 m^3/s in November 2008. However, in December 2008, flood flow was predominant and in January 2009 ebb flow did not attain -1,000 m^3/s.

During February 2011 to December 2011 period, a relatively significant ebb flow occurred, reaching more than -5,000 m^3/s in August 2011.

2.5 Discussion

Morphodynamic changes in the Porto Novo basin and its access channel were investigated by DEM comparisons over 17 years. A 919,600 m² area (divided into 5 rectangular sectors) was analyzed and 19 bathymetric surveys were used. Also, the mean monthly discharge data available from September 2005 to December 2011 were considered.

Erosion and accretion volumes strongly varied in space and time. The northwestern portion of the Porto Novo basin trapped more sediments, while the southeastern portion demonstrated stable behavior or minor deposition rates over time. In the Porto Novo access channel (5E, 5D, 5C, 5B), the 5E area was responsible for the largest deposition rates (Figure 2.8f). Deposition on the convex margin of the channel (western margin of 5E, 5D, and 5C rectangles) was dominant, while the concave margin (eastern margin of 5E, 5D, 5C) showed, most of the time, a stability condition, with depths varying between +0.25 and -0.25 m. Minor deposition rates were found in the 5B rectangle and a stable depth was prevalent in this area.

Environmental conditions favored mostly deposition, although expressively varies in magnitude (Figure 2.8) . Intensive erosion events (April 2001 – May 2001; May 2007 – June 2007; June 2007 – October 2007) associated with high discharge levels were noticed (Figure 2.8, Figure 2.9).

Major deposition volumes were found in the northwestern portion of the Porto Novo basin and in the convex margin of the Porto Novo access channel (Table 2.2). In the northwestern portion of the basin, the enlargement of the channel width decreases the streamflow velocity during ebb flow, providing a favorable condition for sedimentation. Flux predominantly enters the basin through a narrow channel (~130 m width) in the northwesternmost location (Figure 2.2).

The Porto Novo access channel exhibits a convex margin next to a shoal area, called Coroa do Boi, where 0.5 m mean depth is observed (Figure 2.2). The natural morphology in this location presents a width increment between the Porto Novo basin region and the Porto Novo access channel region, what can contribute to decreasing streamflow during ebb conditions, which are predominant in the Patos Lagoon (Figure 2.9). Centrifugal acceleration plays a key role, as flow is fastest on the outside (concave margin) and slowest on the inside (convex margin) (Earle, 2015; Paiva et al., 2020). Restrepo et al. (2020) commented that deep depths next to a shallow area can promote slide-slope instability, generating a lateral flux of sediments, and also increase saltwater intrusion during low streamflow, allowing sediment trapping in the deep channel. Fernandes et al. (2005) described that when a deep channel is next to shallow water, a lens of salt water propagates landward at the bottom of the channel and generates lateral stratification in the adjacent shallow water. Fernandes et al. (2007) presented the horizontal distribution of salinity and flow velocity during flood conditions for this region, where can be observed that flood currents caused by wind from the south quadrant drove salinity excursion into the main channel of the estuary and, under these circumstances, the flow velocity is reduced in the convex margin of the access channel and in the Coroa do Boi area.

The southeastern part of the basin, the concave margin of the access channel, and the 5B area presented a relatively stable condition over time. Historical data demonstrated that the 5B area is a natural channel, where this magnitude of depth was observed since 1875 (Calliari, 1980).

A remarkable erosion event was observed from May 2007 to October 2007 (Figure 2.6a,b, Figure 2.8c), when the ebb flow was higher than 4,000 m^3/s over 5 months (Figure 2.9). From June 2007 to October 2007, the total net volume was -585,662 m^3 (4.43 months) (Table 2.2, Table 2.3). The continuous behavior of high discharge levels only was observed in this period (Figure 2.9). Increased streamflow velocity and bottom shear stress as a consequence, promote sediment scouring. According to Restrepo et al. (2020), progressive sedimentation increases currents in the estuary until they are strong enough to avoid additional sedimentation and promote sediment erosion. In this event, rather than shallower depths, strengthening current velocity flushed sediment out of the area.

In the following months (November 2007 to February 2008), mean monthly discharge levels were reestablished to values around 1,000 m^3/s and flood condition was dominant in March 2008 (Figure 2.9). From October 2007 to March 2008, the total net volume was +594,464 m^3 (Table 2.2, Table 2.3). Reduced discharge levels followed by flood dominant conditions and minor current velocity at the bottom due to deepening depths promoted favorable conditions for siltation. In ebb-dominant estuaries, the transition between the dominance of ebb flow to flood flow favors a quasi-equilibrium dynamic state when siltation occurs (Restrepo et al., 2020). Although it was a natural erosion, it is known that deeper depths promote a decreased current velocity at the bottom, favoring siltation (Martelo et al., 2019).

Regional climate and hydrological cycles control estuarine circulation patterns and salinity levels in the Patos Lagoon estuary (Calliari et al., 2008). When the discharge is higher than 4,500 m^3/s, only strong winds can promote intrusion of salt water, but wind velocity higher than 10 m/s represents less than 1% of cases (Tomazelli, 1993; Möller and Castaing, 1999). With this condition acting during a considerable time interval, sediments are flushed out of the Porto Novo basin and its access channel.

During periods when flood flow or lower ebb flow is noticed, e.g. between January 2006 and June 2006 (Figure 2.9), geometric characteristics were the principal factor that caused favorable hydrodynamics conditions for deposition in the northwestern portion of the Porto Novo basin and in the convex margin of the access channel (Figure 2.5c). Other locations did not present significant variations in depth at this situation. Although total net volumes vary in magnitude, the same tendency of bed processes is observed in the period between February 2011 to December 2011 and also from January 2009 to May 2009 (Figure 2.9, Figure 2.7a, Figure 2.6e). From December 2011 to March 2012 (Figure 2.7b), depositional trends in the same locations are also noticed and, although discharge data from ANA were not available for this period, António et al. (2020) presented discharge levels for this period, and no values higher than 2,500 m^3/s were found due to La Niña event.

Data comparison for March 2008 to January 2009 and from February 2011 to December 2011 (approximately 10 months), demonstrated a similar condition in the deposition patterns (Figure 2.6d, Figure 2.7a) and net volumes (Figure 2.8c,d). Sedimentation induced by flood dominance periods in the first interval could be balanced by discharge peaks over 4,000 m^3/s (Figure 2.9), resulting in a total net volume of +89,159 m^3, whereas the total net volume was +90,868 m^3 from February 2011 and December 2011 (Table 2.2, Table 2.3).

In the inter-dredging period 2, Porto Novo basin dredging finished in April 2004 and Porto Novo access channel dredging finished in May 2004. According to Martelo et al. (2019), the largest volume is expected to be deposited immediately after dredging because deepening depths promote lower current velocity at the bottom. However, the period between January 2006 and June 2006 was the most representative in terms of deposition volumes during the inter-dredging period 2, with a total net volume of +283,584 m^3 for the Porto Novo basin and its access channel (Table 2.2, Table 2.3, and Figure 2.8b). These data highlight the importance of estuarine circulation to determine bed morphology evolution, as it can naturally erode sediments and then deposit a representative load of sediments that enters the area.

The importance of hydrological settings is reinforced when data from equal time intervals are compared. From July 2004 to June 2006 (Figure 2.8b), the total net volume was +462,748 m^3 over 23.07 months (Table 2.2, Table 2.3). From May 2007 and May 2009 (Figure 2.8c), the total net volume was +95,479 m^3 over 23.87 months (Table 2.2, Table 2.3). This difference is related to the largest erosion event registered over 17 years (from May 2007 to October 2007), which controlled siltation rates in the last case, when intensive freshwater discharge remained over 6 months (Figure 2.9).

Hydrological conditions, mainly when discharge exceeds 4,000 m^3/s over long periods, geometric characteristics, and hydrodynamics factors are controller parameters to define siltation rate magnitude in the Porto Novo basin and its access channels. The curvature, the presence of shoal areas, and the morphology around the channel played a key role. Although there is a relation between suspended sediment concentration and river discharge patterns in the Patos Lagoon (Távora et al., 2019; Bitencourt et al., 2020), the single availability of sediments during high discharge levels (>4,000 m^3/s) was not capable to increase siltation patterns, since hydrodynamic conditions did not allow sedimentation in this area, as observed mainly in the period between May 2007 and October 2007.

An ample understanding of the morphodynamics of channels requires investigating *in situ* information to identify sedimentation patterns and cycles (e.g., Restrepo et al., 2020; Rahman and Ali, 2022; Han et al., 2022; Manzolli et al., 2022). Data analysis of the Porto Novo basin and its access channel allow the identification of sedimentation processes in a channel located in the estuarine area of the largest choked lagoon in the world (Kjerfve, 1986) whose hydrodynamics is controlled by freshwater discharge and wind forces, and tidal energy is reduced. We observed the role of geometric characteristics and the morphology around the channel on the hydrodynamics and on the sedimentation processes, as a consequence. Also, the magnitude of discharge during time intervals can expressively control siltation processes.

2.6 Conclusions

Bathymetric and hydrological data analysis allowed the identification of sedimentation patterns in the Porto Novo basin and its access channel located in the microtidal estuary of Patos Lagoon. Channel configuration represented a key factor to define the spatial variations of sedimentation processes because it influenced hydrodynamic conditions. The curvature, the presence of a shoal region next to the channel, and the morphology of the region where the channel is located were the main characteristics observed.

Major siltation rates were observed in the northwestern portion of the basin and in the convex margin of the access channel (western margin), mainly in the 5E sector. Comparison between the first and the last DEM of each inter-dredging period allowed the characterization that 42.4-86.3% of positive net volume for each period corresponded to sediment trapped in the basin and 5E areas. The southeastern portion of the basin, the concave margin (eastern margin) of the Porto Novo access channel, and the 5B sector presented a relatively stable condition. Results suggest that modifications in channel configuration can reduce dredged volumes, as siltation decreases.

Hydrological conditions, especially when the ebb flow exceeds 4,000 m^3/s over long periods, may strongly control the siltation magnitude in the Porto Novo basin and its access channel. For example, from June 2007 to October 2007, 585,662 m^3 of sediments were naturally eroded from the system due to high discharge levels. In the following period, between October 2007 and March 2008, the net volume reached +594,464 m^3 when minor discharge levels and even flood behavior were observed. Therefore, planning dredging, and designing ports must consider a substantial timescale to predict such variations.

Acknowledgments

The authors are grateful to the Rio Grande Port Authority (Portos RS), especially to Mario Dutra, Sávio Novo, and Karen Hartmann for providing bathymetric data and technical information. We are also grateful to Léo Afraneo Hartmann for technical support in writing this article and for review. We thank Elaine Siqueira Goulart for giving support for bathymetric data and Osmar Olinto Möller Junior for giving support for hydrological data. The authors would like to acknowledge CNPq (National Council for Scientific and Technological Development - Brazil) for sponsoring the first author (M.J.B.d.S.).

Funding

This work was supported by CNPq (National Council for Scientific and Technological Development - Brazil).

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CAPÍTULO 3

ARTIGO 2

SEDIMENT PATTERNS IN THE NAVIGATION CHANNEL OF THE PATOS LAGOON ESTUARY, BRAZIL, BETWEEN 2005 AND 2009

Submetido ao periódico Continental Shelf Research (ANEXO B).

3. SEDIMENT PATTERNS IN THE NAVIGATION CHANNEL OF THE PATOS LAGOON ESTUARY, BRAZIL, BETWEEN 2005 AND 2009

Marine Jusiane Bastos da Silva[a,*], Iran Carlos Stalliviere Correa[a], José Antonio Scotti Fontoura[b] and Christian Garcia Serpa[b]

[a]Federal University of Rio Grande do Sul, Campus do Vale, Av. Bento Gonçalves, 7712 - Agronomia, Porto Alegre, Rio Grande do Sul, 91540-000; marinebastos@yahoo.com.br; iran.correa@ufrgs.br

[b]Federal University of Rio Grande, Campus Carreiros, Av. Itália, s/n - km 8 - Carreiros, Rio Grande, Rio Grande do Sul; scottifontoura@gmail.com; christianserpa@yahoo.com.br

*Corresponding author: marinebastos@yahoo.com.br

Abstract

Numerous ports worldwide are located in estuaries, where siltation is often a significant challenge that restricts navigation. Therefore, understanding sediment patterns in ports is fundamental for improving waterway maintenance. In the southernmost region of Brazil, a major channel functions as the unique link between Patos Lagoon and the Atlantic Ocean. The channel stretches from the estuary to the inner continental shelf and serves as the unique maritime access point to the Port of Rio Grande. Regular dredging is necessary to maintain navigability. This study aims to evaluate the morphological evolution, characteristics, and sedimentation patterns of the channel between 2005 and 2009, prior to the channel deepening and modifications made to the jetties that fix the mouth of the inlet. We utilized Digital Elevation Models generated from bathymetric data supplied by the Port Authority and discharge data from the Patos Lagoon inlet. The analysis revealed a correlation between discharge levels and net sedimentation rates. Within the inner channel, high ebb flow was linked to lower net sedimentation rates, whereas low ebb flow and flood flow were associated with higher net sedimentation rates. However, in the marine domain section of the channel, no significant correlation between siltation and discharge was detected. Several points along the channel exhibit significant natural depths, with some exceeding 16 meters, particularly the mouth of the inlet, which is influenced by hydrodynamic conditions. The

east margin of the inner channel, the area between the jetties, and the segment of the channel situated in the marine domain have a tendency to accumulate sediments, although the degree of siltation varies both spatially and temporally.

Keywords: Patos Lagoon, sediment dynamics, siltation, discharge.

3.1 Introduction

Siltation is a prevalent problem in navigation channels worldwide, mainly linked to the quiescent hydrodynamic conditions required for these areas (Winterwerp, 2005; Van Rijn, 2016). The decrease in depth caused by sediment deposition appears to be correlated with the harbor entrance's geometric configuration, as well as the physical and environmental conditions (Van Rijn, 2016).

The most commonly used method for maintaining safe navigation and preserving depths over time is dredging. However, as this process increases operational costs and needs to be carried out regularly, strategies to prevent siltation are becoming increasingly important (Hughet et al., 2020). Some techniques aim to reduce sedimentation by optimizing port design and minimizing the basin's trapping efficiency (Hughet et al., 2020; Kirichek et al., 2021). Understanding sedimentation patterns over time is fundamental to achieving these objectives. Retrospective analyses of channel morphology through bathymetric surveys can provide valuable insight into depositional processes in coastal and estuarine regions (Monge-Ganuzas et al., 2013; Cattani and Lamour, 2016; Yang et al., 2019; Zhang et al., 2022).

Due to estuarine characteristics, many ports worldwide are located in estuaries, such as Rotterdam, Antwerp, New York, Hamburg, and Lisbon (Prumm and Iglesias, 2016; Franzen et al., 2023), making estuaries an important route for international commerce. Several studies have been conducted to understand sediment dynamics in ports located in estuaries (Winterwerp, 2005; Cattani and Lamour, 2016; Mayerle et al., 2015; Silva et al., 2015; Van Rijn, 2016; Restrepo et al., 2020; da Silva et al., 2022). Exploring the morphological evolution of navigation channels contributes to a better understanding of the sedimentation pattern and helps improve strategies to minimize siltation.

Patos Lagoon, one of the largest coastal lagoons in the world, is located in the southernmost part of Brazil. This lagoon is connected to the Atlantic Ocean through a single narrow channel. The channel extends from the estuarine area to the adjacent continental shelf, and it is a good laboratory for understanding the sedimentation patterns in long channels. It is the maritime access to the Port of Rio Grande infrastructure, and regular maintenance dredging is required to guarantee navigation. The Port of Rio Grande is one of the principal ports in Brazil. In 2022, it handled over 37 million tons of cargo (PORTOS RS, 2023), which further enhanced its social and economic significance.

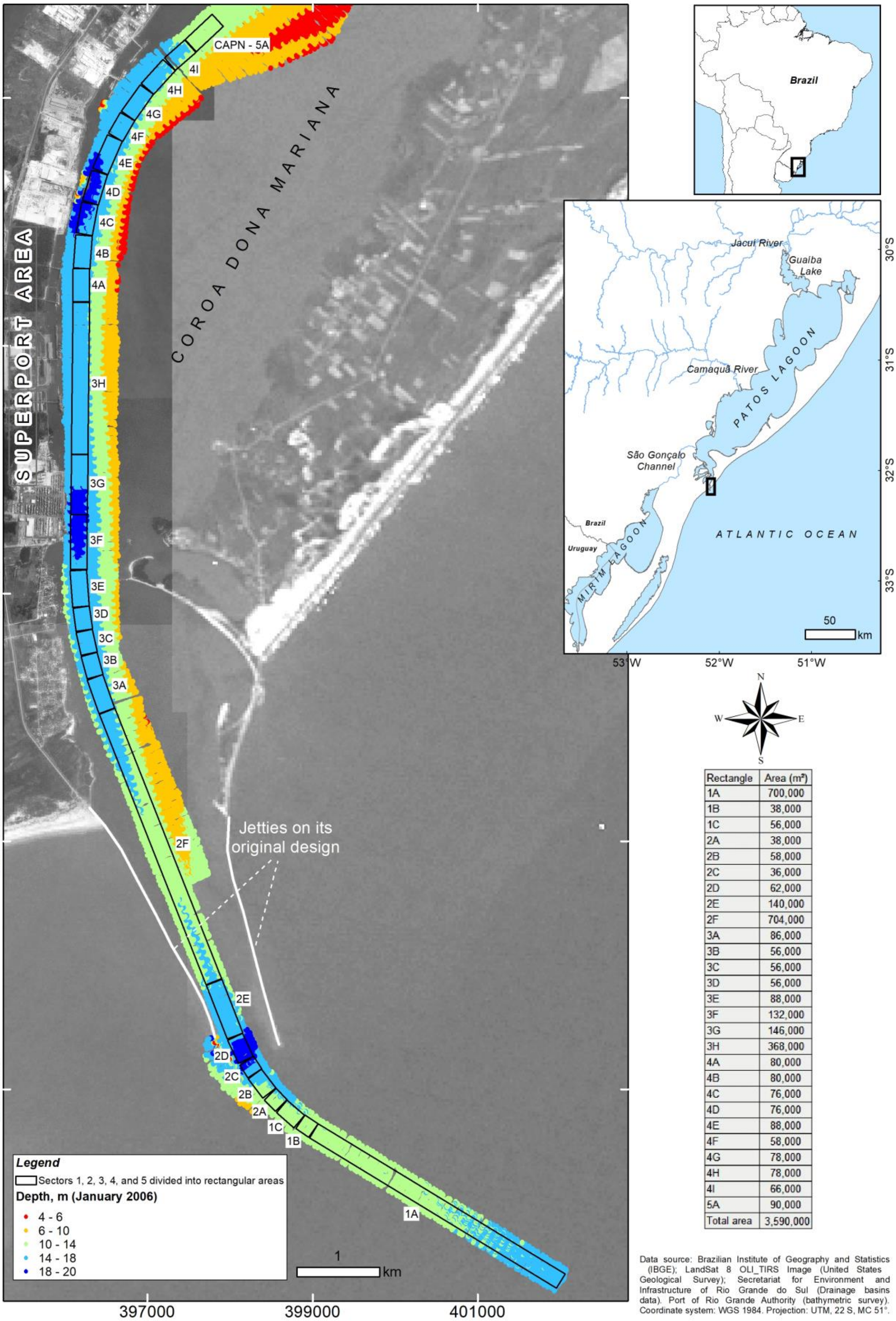
Several studies have been carried out to understand the hydrodynamics, sediment dynamics, and estuarine circulation of the Patos Lagoon estuary (Möller et al., 2001; Fernandes et al., 2005; Calliari et al., 2008; Barros et al., 2014; Silva et al., 2015; Távora et al., 2019; António et al., 2020; Bitencourt et al., 2020; Franzen et al., 2023). Despite its significant relevance and contribution, previous studies have not widely focused on sedimentation patterns in the access channel of the Patos Lagoon estuary, and bathymetric data series have not yet been taken into account.

Therefore, this study aims to examine the morphological evolution of the access channel to the Port of Rio Grande prior to the modifications in geometric settings carried out in 2009 and 2010. We have considered bathymetric data from 2005 to 2009 and discharge data of Patos Lagoon to support the bed morphology analysis, as it is one of the main drivers of Patos Lagoon circulation (Moller and Castaing, 1999; Moller et al., 2001; Távora et al., 2019; António et al., 2020). A comprehensive understanding of bed variability over time and space is essential to identify the factors that contribute to increase siltation in ports. These data support the search for appropriate procedures to mitigate and control sediment deposition, making ports more sustainable.

3.2 Study area

The Patos Lagoon is the largest choked lagoon in the world, with a surface area of 10,360 km² (Kjerfve, 1986). It is the dominant feature in the coastal plain of the Rio Grande do Sul state, in the southernmost part of Brazil. The estuarine area comprises approximately 10% of the lagoon area (Möller et al., 2001). A single narrow channel links Patos Lagoon to the Atlantic Ocean (Calliari et al., 2008). The Port of Rio Grande infrastructure is located on the west margin of this channel (Figure 3.1). The Port Authority divided the channel into six sectors. From 2005 to 2009, Sectors 1 to 4 were dredged to a depth of 14 m, while Sectors 5 and 6 were dredged to a depth of 10.5 m.

The mouth of the inlet is fixed by two long jetties constructed in the early 1900s, which were extended in 2009 and 2010. The channel's configuration and depths in Sectors 1 to 5 were also modified during this time to allow the navigation of larger vessels. In this study, we focused on the sectors where geometric and depth settings were modified between 2009 and 2010: sectors 1, 2, 3, and 4, as well as only the southernmost part of the Porto Novo Access Channel (Sector 5), which is called "CAPN – 5A" in this study. After 2010, the Port Authority's identification of these sectors also changed, as the channel was extended towards the sea. We used the identifications applied by the Port Authority before 2009 and divided the area into 27 rectangles arranged according to the orientation of the channel's main axis (Figure 3.1).



Rectangle	Area (m²)
1A	700,000
1B	38,000
1C	56,000
2A	38,000
2B	58,000
2C	36,000
2D	62,000
2E	140,000
2F	704,000
3A	86,000
3B	56,000
3C	56,000
3D	56,000
3E	88,000
3F	132,000
3G	146,000
3H	368,000
4A	80,000
4B	80,000
4C	76,000
4D	76,000
4E	88,000
4F	58,000
4G	78,000
4H	78,000
4I	66,000
5A	90,000
Total area	3,590,000

Figure 3.1: Study area. Sectors 1 (1A – 1C), 2 (2A – 2F), 3 (3A – 3H), 4 (4A – 4I), and 5 (CAPN – 5A) were divided into rectangular areas.

Long and Paim (1987) described the evolution of the channel as being driven by fluvial processes, characterized by the migration of two meanders towards the margins of the channel. This migration leads to erosion on the concave margins of the channel. According to the authors, the downstream meander, which corresponds to Sector 4 (Figure 3.1), moves towards the west margin of the channel, promoting erosion, while the convex margin (Coroa Dona Mariana, a shallow area) increases in size. The accretion of Coroa Dona Mariana occurs due to the deposition of sand during periods of landward flow in the estuary, which is promoted by low rainfall in the hydrographic basin and strong southward winds (Long and Paim, 1987).

The Patos Lagoon hydrodynamics is controlled by the combination of wind action and river discharge (Moller and Castaing, 1999; Moller et al. 2001). The prevailing winds are from the northeast (NE) and southwest (SW) directions, with the same orientation as the lagoon axis. NE winds dominate throughout the year and result in seaward flow in the estuary, while SW winds are particularly important during the austral autumn and winter due to frontal systems, leading to landward flow (Moller et al. 2001; Fernandes et al., 2002). Garcia et al. (1997) note that hydrological/riverine cycles are key to estuarine hydrography. Moller and Castaing (1999) and Moller et al. (2001) indicate that freshwater discharge is affected by the flow patterns of the rivers comprising the Patos Lagoon drainage basin, which experience high discharge in late winter and early spring and low to moderate discharge in summer and autumn (southern hemisphere). Interannual variability is also observed, with discharge exceeding average values during El Niño events (Garcia et al., 1997). According to Barros et al. (2014), freshwater discharge plays an extremely significant role in controlling estuarine hydrodynamics at longer time scales, ranging from months to years or more.

Kjerfve (1986) described Patos Lagoon as a freshwater system with an estuarine area restricted to the southernmost part of the lagoon. The extent of saltwater intrusion depends on wind and freshwater patterns (Moller et al., 2001), and ebb flows are predominantly in the estuary (Calliari et al., 2008; Barros et al., 2014).

Calliari et al. (1997) analyzed the distribution of bottom types in the Patos Lagoon estuary. According to the results shown by the author, Sectors 3 to 5 had silty clay sediments in the main axis surrounded by silty sand and sand in the adjacent shoal areas. Furthermore, high current velocities of seawater inflow cause the deposition of sandy marine sediments in the lower estuary, particularly in the area between the jetties (Calliari et al., 1997; Antiqueira and Calliari, 2005).

3.3 Materials and methods

3.3.1 Bathymetric data

The analysis of bed evolution considered bathymetric data provided by the Port Authority (Portos RS). We selected 11 bathymetric surveys that were standardized to the WGS 1984 datum (Table 3.1). Digital elevation models were generated using the Kriging method in Surfer software, which is known for its flexibility.

Table 3.1: Selected bathymetric surveys provided by the Port Authority (PORTOS RS).

Bathymetric surveys	Date range of data acquisition (month/day/year)	Coverage area
March 2005	03/10/2005 – 03/13/2005	Entire channel
June 2005	06/28/2005 – 06/29/2005	1B – 1C; 2A – 2F; 3A – 3G
January 2006	01/07/2006 – 01/11/2006	Entire channel
June 2006	06/01/2006 – 06/02/2006	4A – 4I; 5A - CAPN
August 2006	08/09/2006 – 08/11/2006	1A – 1C; 2A – 2F
October 2006	10/11/2006 – 10/18/2006	1A – 1C; 2A – 2F
June 2007	06/10/2007 – 06/12/2007	1A – 1C; 2A – 2D
October 2007	10/20/2007 – 10/23/2007	Entire channel
March 2008	03/08/2008 – 03/11/2008	Entire channel
January 2009	01/07/2009 – 01/08/2009	Entire channel
May 2009	04/30/2009 – 05/02/2009	Entire channel

We applied the same method proposed by Bastos da Silva et al. (2023) to analyze the morphological evolution of channels and siltation through bathymetric data. In the software Surfer, the Kriging method generated rectangular grids with horizontal rows and vertical columns. Due to the channel curvature, this procedure could generate grid points outside the limits of the channel (Figure 3.2a,b).To prevent extrapolation of the channel limits, we divided each sector of the channel into rectangular areas. Afterward, we rotated each rectangle and its bathymetric dataset so that the base is horizontal (considering the θ angle), and we generated the DEMs using this configuration (Figure 3.2c). Finally, each DEM was rotated back to its original position (Figure 3.2d).

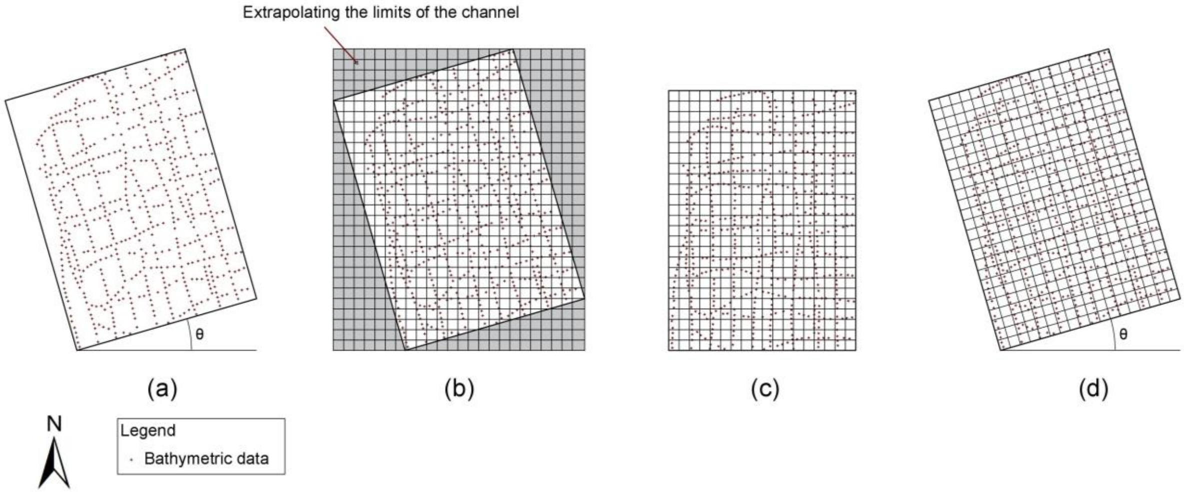


Figure 3.2: Methodology description, based on Bastos da Silva et al. (2023): (a) Bathymetric data confined within a rectangular area. (b) Grid generation considering the original position of the dataset, which results in grid points extending beyond the channel/rectangular area limits (gray area). (c) Grid generation after rotating the rectangular area, where grid limits are confined to the area of interest. (d) Rotation of the grid to the original position of the rectangular area.

The rectangular areas were defined based on the following main aspects: (i) not extrapolating the limits of each sector (1, 3, 4, and 5); and (ii) the channel orientation. As shown in Figure 3.1, we obtained three rectangles in Sector 1 (1A-1C), six rectangles in Sector 2 (2A-2F), eight rectangles in Sector 3 (3A-3H), nine rectangles in Sector 4 (4A-4I), and one rectangle in Sector 5 (CAPN-5A). In total, we generated 297 DEMs, which corresponded to 11 bathymetric surveys for each of the 27 rectangular areas. This procedure allowed the generation of regular grids with a 10m cell size, in which the columns are parallel to the main axis of the channel, and the rows are perpendicular to the main axis (Figure 3.2d).

The comparison between DEMs of each rectangular area allowed the identification of volumes of sediment deposition and erosion during a certain time interval. The net volumes were calculated by subtracting the eroded volume from the deposited volume. Net sedimentation rates were obtained by dividing the net volume by the time interval between the respective DEMs and by the planar area of each rectangle (Bastos da Silva et al., 2023). Additionally, the subtraction of the coordinate z (depth) of the DEMs was used to create maps of bed variability over time, which were useful for identifying spatial sedimentation patterns (Bastos da Silva et al., 2023).

Based on the data and information provided by the Port Authority, no dredging activities occurred during the time intervals in which the DEMs were compared. From 2005 to 2009, dredging activities were carried out in the following sectors: Sector 1, from March 2007 to May 2007; Sector 2, from November 2006 to May 2007; Sector 4, in November 2006. No dredging was registered in Sector 3 during this period. Therefore, we aimed that only the natural removal of sediments was considered in this study.

3.3.2 Hydrological data

To support the temporal analysis of bed variability, we considered the average monthly discharge data of the Patos Lagoon estuary. These data were available on the website of the National Water and Sanitation Agency of Brazil (ANA, www.hidroweb.ana.gov.br). The period from August 2005 to May 2009 was considered in this study. The data were measured at the location of 32.14° S, 52.10° W. Positive values indicate flood flow, while negative values indicate ebb flow.

3.4 Results

3.4.1 Channel characteristics

The six bathymetric surveys covering the entire channel (Table 3.1) were analyzed to identify the channel characteristics based on *in situ* data from May 2005 to May 2009 (Figure 3.3). The main channel was dredged to a depth of 14 m (except for CAPN – 5A, which was dredged to a depth of 10.5 m). Nevertheless, the channel exhibits certain morphological characteristics as a result of sediment dynamics, which will be summarized in this section.

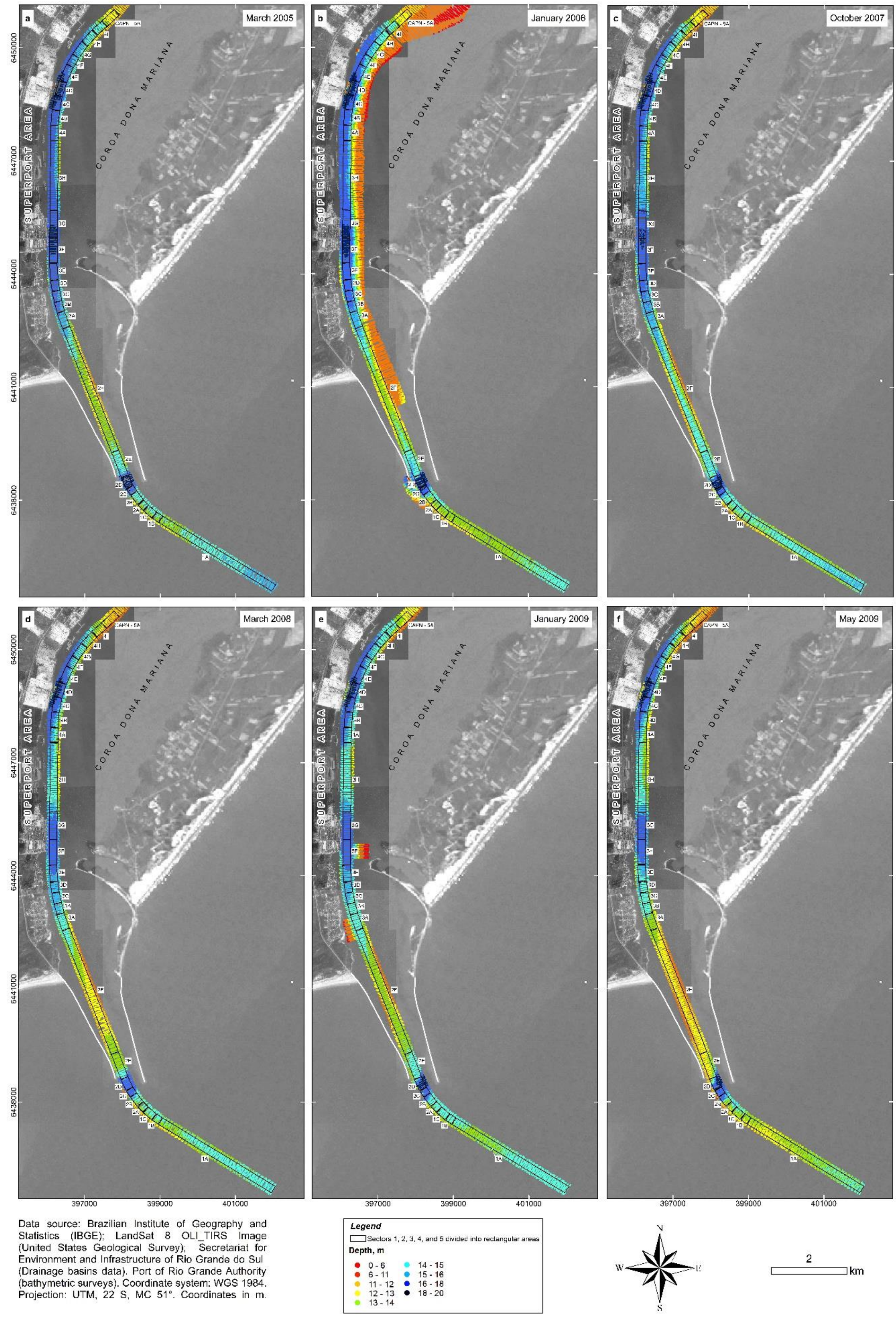


Figure 3.3: Bathymetric surveys of the entire channel (data provided by the Port Authority - PORTOS RS).

In Sector 1, lower depths were observed in the northwestern portion of the 1A rectangle, while deeper depths were found in its southeastern portion (Figure 3.3). In Sectors 1 (1A, 1B, 1C) and 2 (2A, 2B, 2C, 2D), deeper depths were found in the east margin of the channel, which has a convex shape, while lower depths were observed in the west margin of these rectangular areas (Figure 3.3).

In sector 2, the region between the jetties (2F) showed depths lower than 14 m in most cases (Figure 3.3a,b,d,e,f), while the area at the mouth of the inlet (2C, 2D) was characterized by depths greater than 16 m, reaching up to 20 m at points on the east margin of the channel (Figure 3.3). The 2E rectangle marked the transition from greater depths to minor depths in the landward direction. Additionally, the northwestern portion of the 2F rectangle and the 3A rectangle marked the transition from lower depths in Sector 2 to greater depths in Sector 3 in the landward direction. Therefore, minor depths when compared to the surrounding areas (Figure 3.3) described the 2F region.

Based on the analyzed data, sector 3 is characterized by depths greater than 14 m in most cases, with shallower depths occupying the east margin of the channel (Figure 3.3a-f). Depths of up to 18 m were observed in areas 3F and 3G, while area 3H had smaller depths (13-15 m).

Sector 4 is characterized by a concave margin on the west side, where depths reached up to 20 m, particularly in the 4C, 4D, and 4E areas. In the southernmost part of Sector 5, represented by the CAPN-5A rectangle, depths of 11 m to 13 m were observed, despite being dredged to reach a depth of 10.5 m (Figure 3.3).

3.4.2 Temporal and spatial analysis

The temporal and spatial analysis of sediment balance was based on comparing DEMs of the same area at different times. We also considered the average discharge of Patos Lagoon to understand the correlation between sediment deposition/erosion and lagoon discharge. Bastos da Silva et al. (2023) also applied this procedure to other parts of the channel.

Based on the available data (Table 3.1), we considered 10 time periods: March 2005 - June 2005, June 2005 - January 2006, March 2005 - January 2006, January 2006 - August 2006, January 2006 - June 2006, August 2006 - October 2006, June 2007 - October 2007, October 2007 - March 2008, March 2008 - January 2009, and January 2009 - May 2009. We combined DEMs obtained from bathymetric surveys that covered only some sectors or areas to make the best use of the available data and refine the analysis.

For each time interval and rectangular area, we calculated the net sedimentation rate by dividing the net volume (deposited volume minus eroded volume) by the area of the rectangle and by the time interval (in months) between the older and newer DEMs (Figure 3.4). A positive value indicates that the deposited volume is greater than the eroded volume, while a negative value indicates the opposite. For example, from March 2005 to June 2005 (Figure 3.4a), the net sedimentation rate was 14.62 cm/month in the 1B area (indicating deposition), while it was -3.79 cm/month in the 3D area (indicating erosion).

The subtraction of DEMs also allowed the identification of regions where sediment tends to accumulate. The maps of each period are presented in Figure 3.5, Figure 3.6, Figure 3.7, and Figure 3.8. The regions where sediment deposition occurred are represented in red, while the regions where sediment erosion occurred are represented in blue. Variations within ±0.5 m were considered stable, and the respective color was represented with some transparency.

Aiming to identify a possible correlation between bed deposition/erosion and the discharge of Patos Lagoon, we considered the average monthly discharge of Patos Lagoon, whose data were available on the ANA website (Figure 3.9). Positive values indicated periods of flood flow, and negative values indicated periods of ebb flow, on average. It was observed that ebb flow was predominant from August 2005 to May 2009.

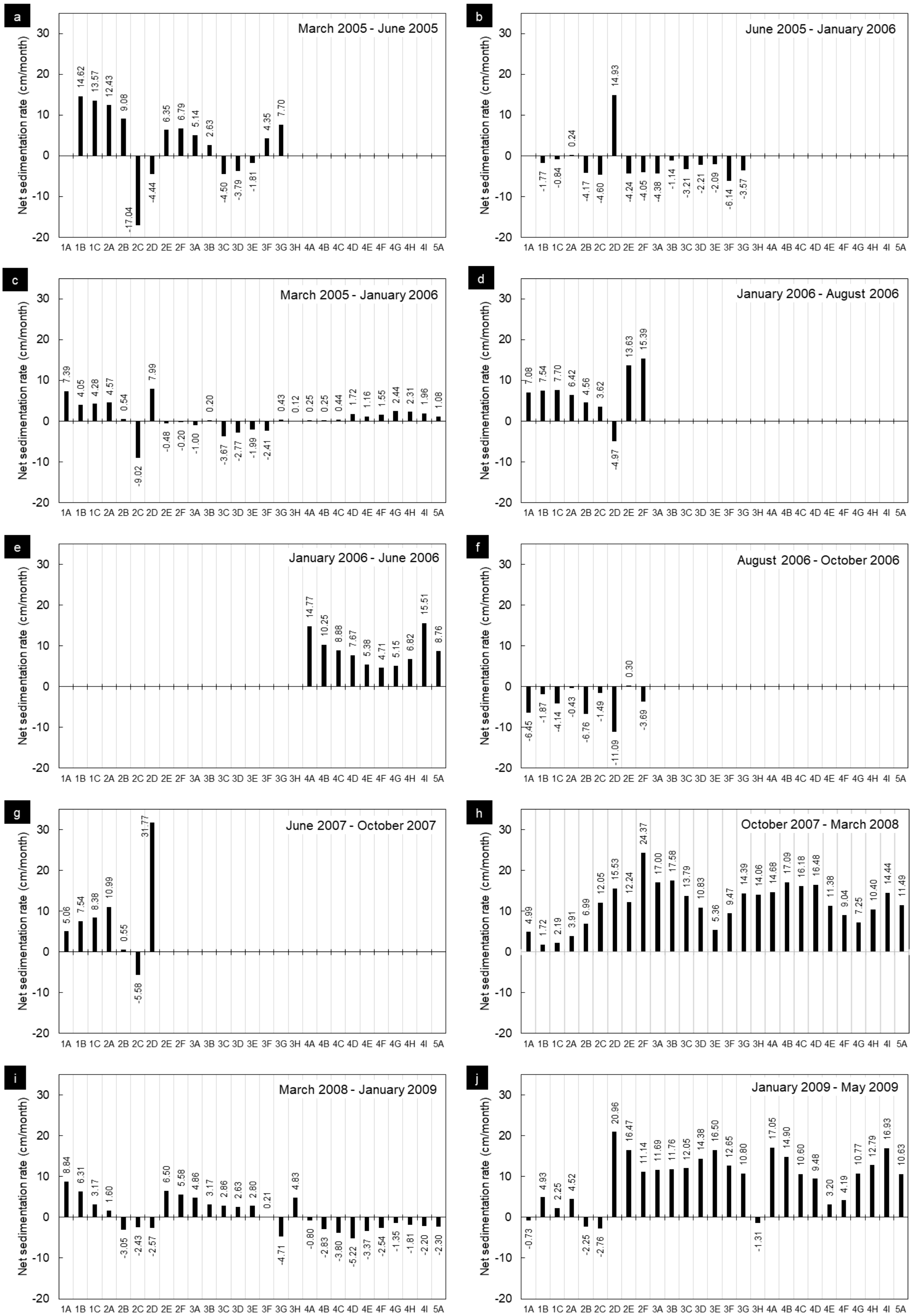


Figure 3.4: Net sedimentation rates for each rectangular area based on available bathymetric data. Positive values indicate the predominance of deposition, while negative values indicate the predominance of erosion.

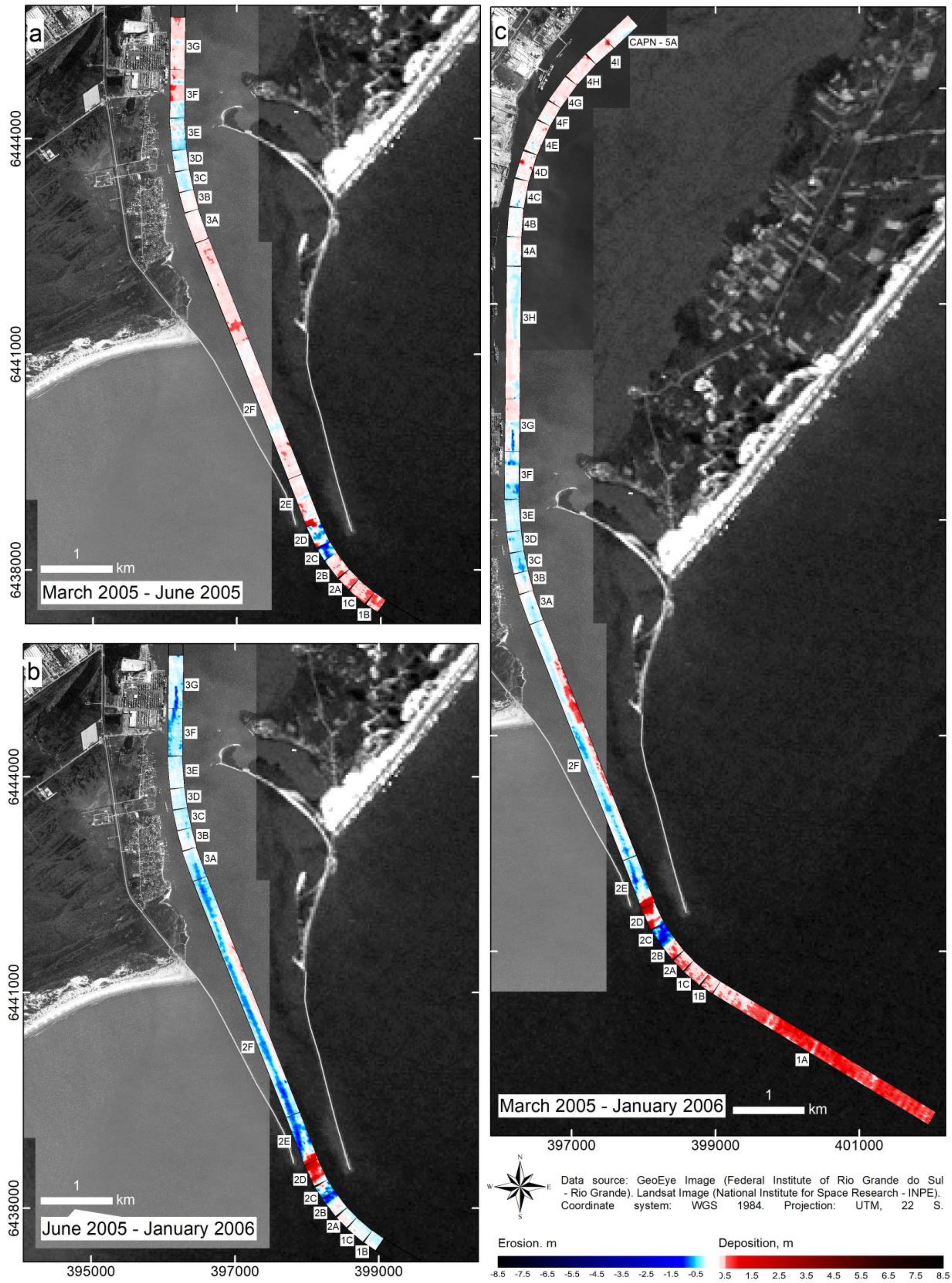


Figure 3.5: Bed evolution from March 2005 to January 2006, obtained by subtracting Digital Elevation Models.

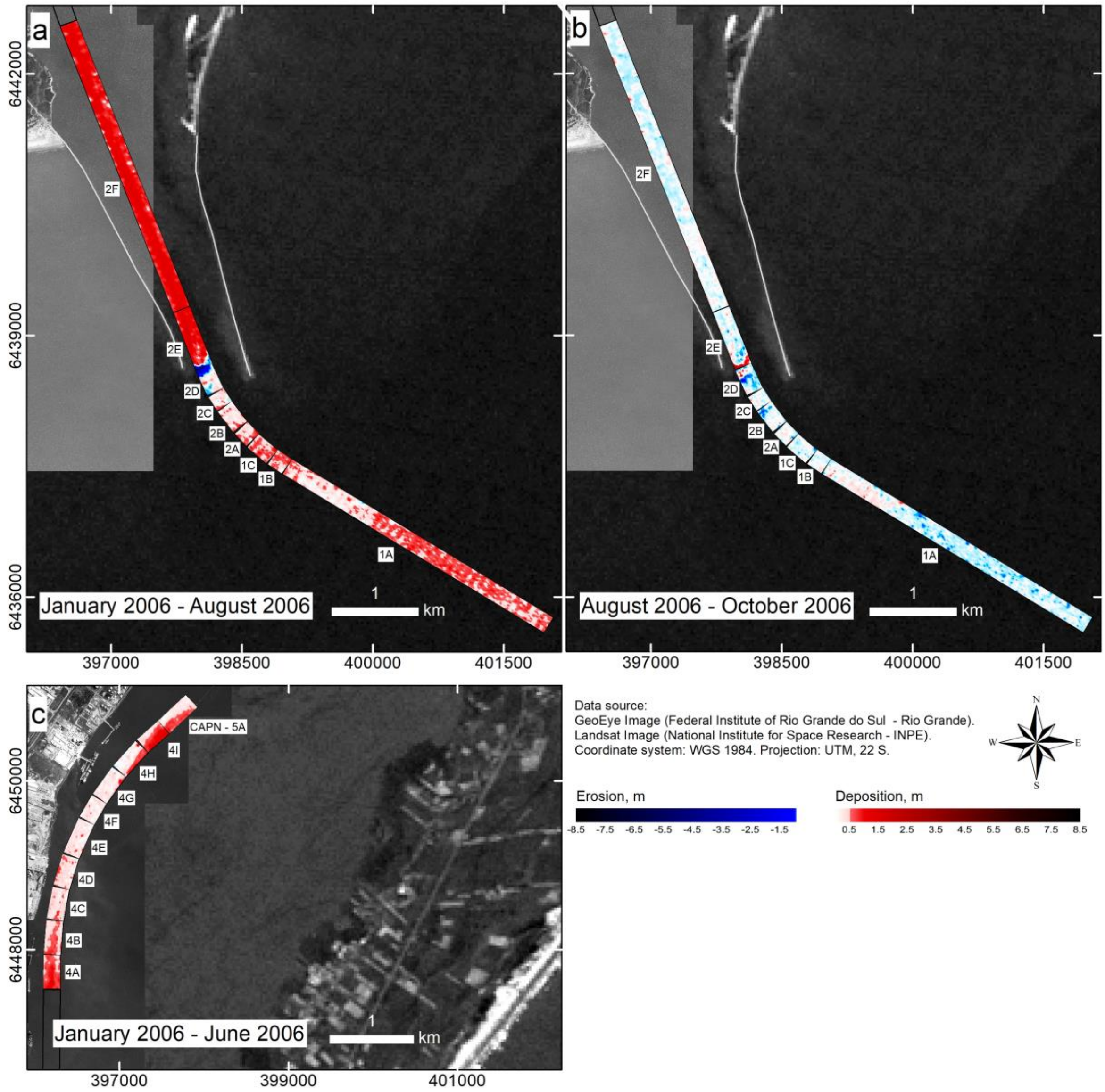


Figure 3.6: Bed evolution from January 2006 to October 2006, obtained by subtracting Digital Elevation Models.

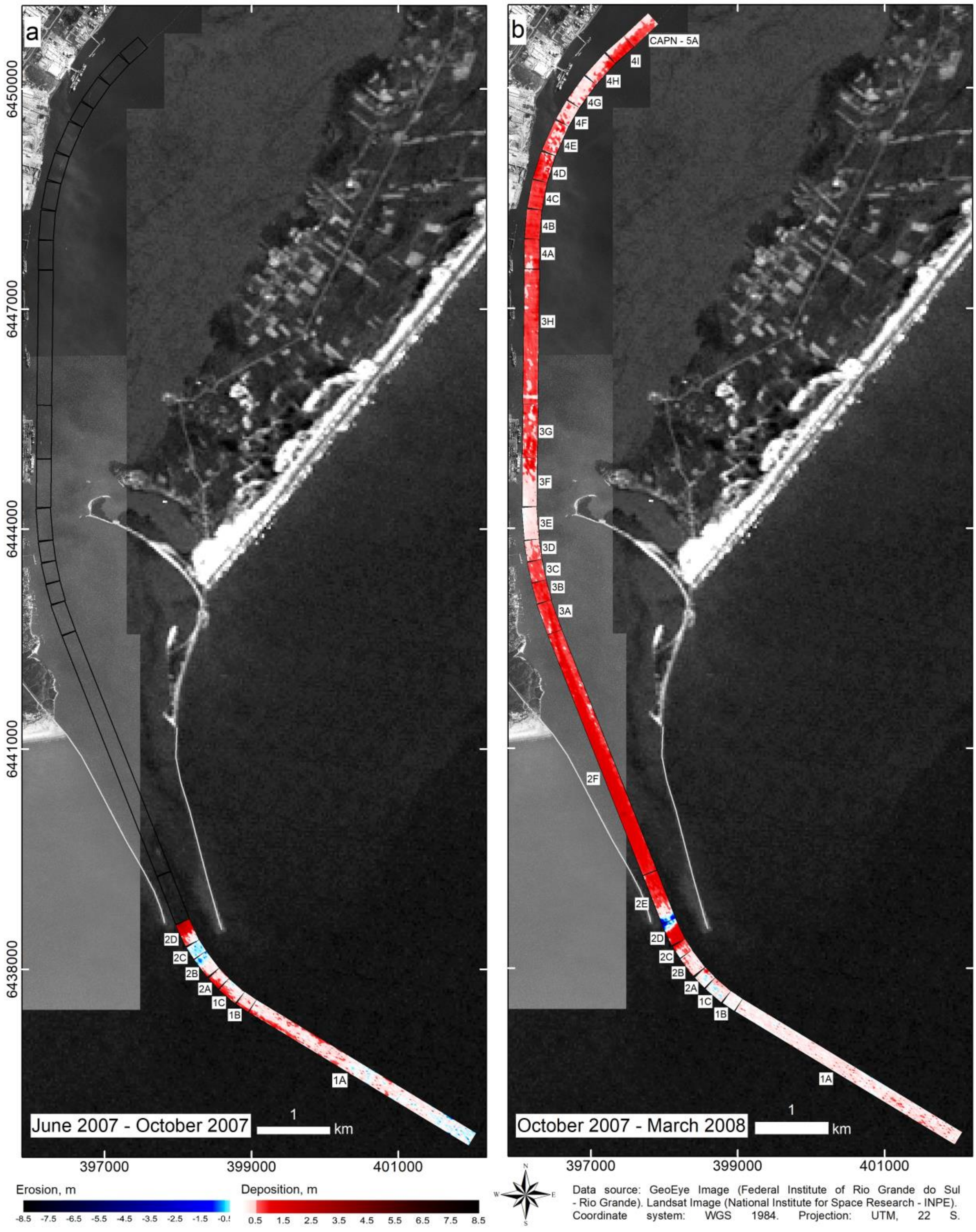


Figure 3.7: Bed evolution from June 2007 to March 2008, obtained by subtracting Digital Elevation Models.

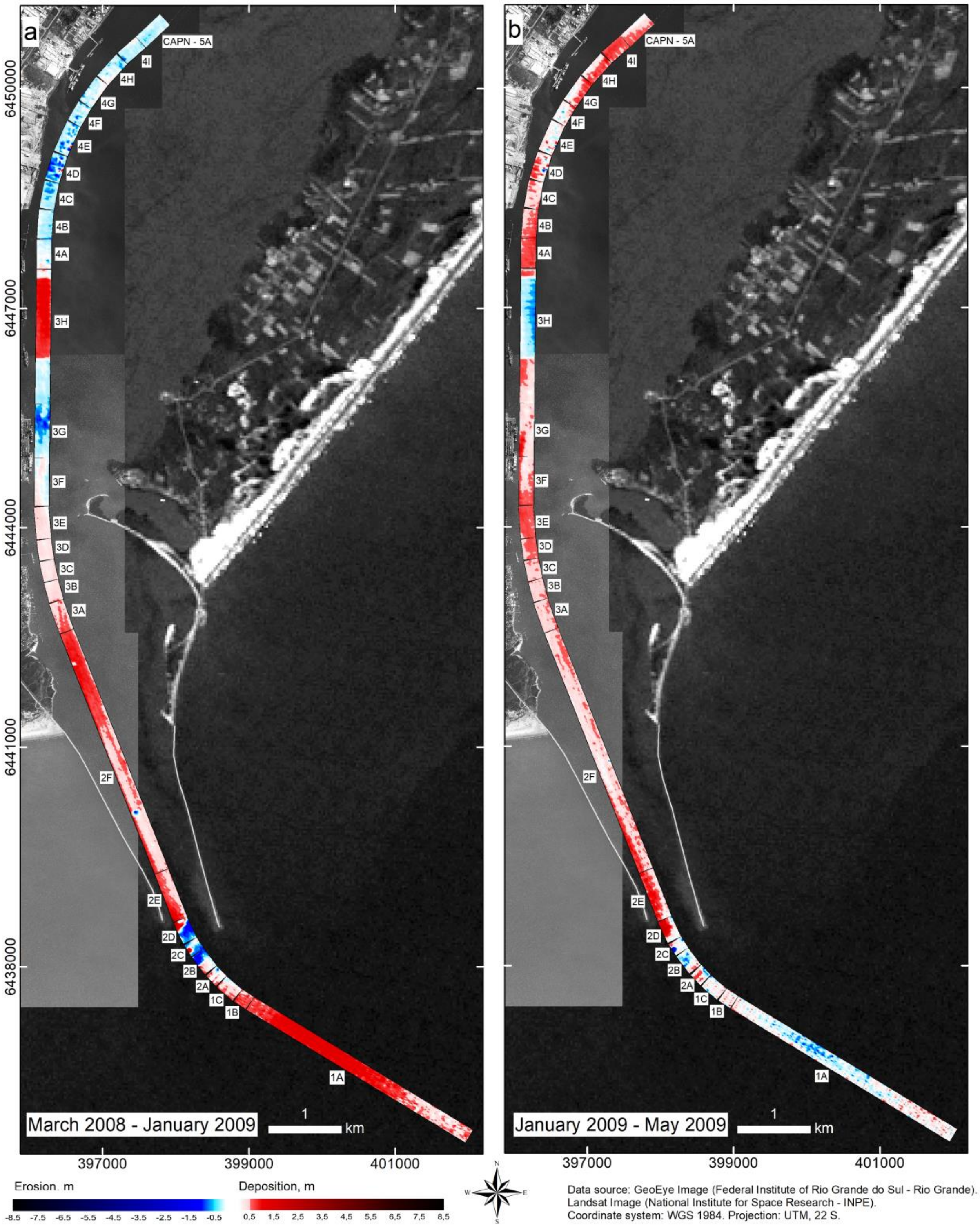


Figure 3.8: Bed evolution from March 2008 to May 2009, obtained by subtracting Digital Elevation Models.

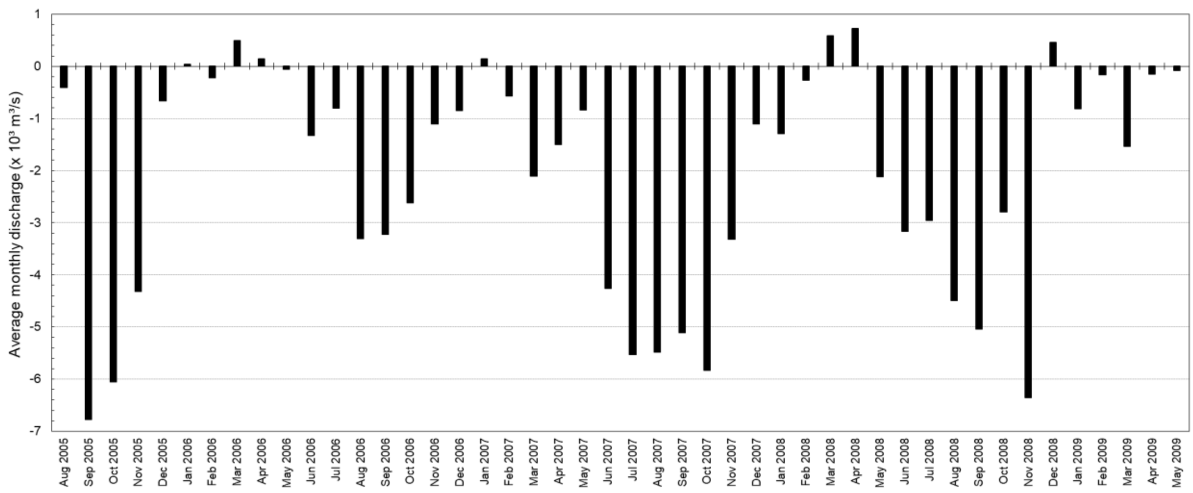


Figure 3.9: Discharge data of Patos Lagoon estuary, obtained from the National Water and Sanitation Agency of Brazil (ANA, www.hidroweb.ana.gov.br). Positive values indicate flood flow and negative values indicate ebb flow, on average.

Analysis of Sectors 4 (4A-4I) and 5 (CAPN-5A)

From March 2005 to January 2006, the net sedimentation rates in Sectors 4 and 5 were positive and small, peaking at a maximum of 2.44 cm/month in the 4G area (Figure 3.4c). The map indicated that sediment deposition caused depths to vary by less than +0.5 m in most points, representing a stable condition (Figure 3.5c). Discharge data were only available for the period between August 2005 and January 2006, during which an intense ebb flux was observed, with the ebb flow reaching almost 7,000 m³/s in September 2005 (Figure 3.9).

From January 2006 to June 2006, net sedimentation rates were higher, peaking at 14.77 cm/month in the 4A area and 15.51 cm/month in the 4I area (Figure 3.4e). The morphological evolution analysis revealed that the majority of the sediment was trapped in the convex margin of rectangles 4H, 4I, and CAPN-5A (east margin), as well as in areas 4A and 4B (Figure 3.6c). During this period, the Patos Lagoon inlet experienced periods dominated by small ebb flow (February 2006, May 2006, and June 2006) and also periods dominated by flood flow (January 2006, March 2006, April 2006) (Figure 3.9).

Before proceeding with the specific analysis of this sector, it is important to note that the period between June 2007 and November 2007 (no bathymetric data available for the sector) was characterized by an intense ebb flow, reaching more than 4,000 m³/s during five consecutive months (Figure 3.9). The intense ebb flow persisted for a relatively long period and lost strength in December 2007. The following months

(January 2008 – February 2008) were marked by weaker ebb flows (around 1,000 m³/s) and by flood flow in March 2008 (Figure 3.9).

The sediment dynamics from October 2007 to March 2008 (Figure 3.4h) demonstrated that Sector 4, like all other sectors, trapped sediments, and a significant siltation process was observed in the entire channel. Most of the sediments were trapped in the 4A, 4B, 4C, and 4D regions, as well as in the east margin of rectangles 4H, 4I, and CAPN-5A (Figure 3.7b). The west border (concave form) of the channel in this sector remained stable (Figure 3.7b).

The ten months between March 2008 and January 2009 were characterized by erosion in Sectors 4 and 5 (Figure 3.4i). The 4D rectangle had the highest erosion rate, while other areas demonstrated slightly lower erosion rates (Figure 3.4i, Figure 3.8a). The average monthly discharge showed an intense ebb flow that persisted from May 2008 to November 2008, reaching more than 6,000 m³/s in November 2008 (Figure 3.9).

From January 2009 to May 2009, a deposition process was mainly observed in the east margin of the following areas: 4A, 4B, 4G, 4H, 4I, and CAPN-5A (Figure 3.4j, Figure 3.8b). The concave margin of this sector presented a stable condition, as depths varied by less than +0.5 in most points. During this period, a weak ebb flow was noticed (Figure 3.9).

Analysis of Sector 3 (3A – 3H)

The region exhibited erosive behavior from June 2005 to January 2006, with the 3A, 3F, and 3G areas showing the highest erosional rates (Figure 3.4b, Figure 3.5b). The discharge data showed that the ebb flow was intense in the last four months before January 2006 (Figure 3.9), reaching over 6,000 m³/s in two consecutive months (September and October 2005). The sediment balance between March 2005 and January 2006 (Figure 3.4c, Figure 3.5c) appears to have been influenced by the behavior observed in the last seven months (June 2005 - January 2006), with small positive net sedimentation rates in the 3B, 3G, and 3H areas and erosive behavior in the other areas (3A, 3C, 3D, 3E, and 3F).

For the period from October 2007 to March 2008, the highest net sedimentation rates of all the analyzed periods were observed (Figure 3.4h, Figure 3.7b). The areas 3D, 3E, and 3F exhibited the smallest net sedimentation rates, and the depth variation did not exceed +0.5 m at most points in these regions (Figure 3.7b). The discharge weakened during this period (Figure 3.9), and a depositional stage was observed throughout the channel (Figure 3.7b).

The period between March 2008 and January 2009, when an intense ebb flow was recorded (Figure 3.9), resulted in a slight deposition in most parts of Sector 3, with most sediments being trapped in the 3H area and eroded from the 3G area (Figure 3.4i, Figure 3.8a). In the subsequent four months, from January 2009 to May 2009, significant deposition was observed in all rectangular areas except for the 3H area (Figure 3.4j, Figure 3.8b), with a weaker ebb flow noticed (Figure 3.9).

Analysis of Sector 2 (2A – 2F)

Unlike Sectors 3, 4, and 5, Sector 2 did not exhibit the same behavior for all rectangular areas during the same period. The areas experienced varying processes, with deposition patterns observed in one area and erosion patterns in an adjacent area (Figure 3.4a,b,c,d,g,i,j). Sector 2 showed consistent behavior only between August 2006 and October 2006 (Figure 3.4f, Figure 3.6b) and between October 2007 and March 2008 (Figure 3.4h, Figure 3.7b). From August 2006 to October 2006, Sector 3 experienced an erosional stage (Figure 3.4f, Figure 3.6b), with an ebb flow greater than 2,000 m^3/s (Figure 3.9) observed. Between October 2007 and March 2008, when the ebb flow was significantly reduced, and even a flood flow was recorded (Figure 3.9), Sector 2 demonstrated a strong deposition process (Figure 3.4h, Figure 3.7b).

The analysis of net sedimentation rates revealed that the behavior of areas 2E and 2F tended to follow the same trend as Sector 3 (described in the previous section), particularly when considering areas 3A and 3B (Figure 3.4a,b,c,h,i,j). A highly dynamic behavior was observed from rectangle 2D towards the sea. The 2C area exhibited an erosional process in most cases (Figure 3.4a,b,c,f,g,i,j), while the 2D area significantly varied its behavior, presenting intense accretion (Figure 3.4g) and significant erosion (Figure 3.4f) during some periods. Rectangle 2A demonstrated the same behavior as Sector 1 (Figure 3.4), except for the period between June 2005 and January 2006 (Figure 3.4b), during which a slight difference was observed.

Analysis of Sector 1 (1A – 1C)

The analysis of Sector 1 encompassed data from 9 periods of time. Depositional processes predominated in 7 periods (Figure 3.4a,c,d,g,h,i,j). Both depositional and erosional processes were observed in Sector 1 during ebb flows. For instance, from

August 2006 to October 2006, an ebb flow greater than 2,400 m³/s was recorded (Figure 3.9), and Sector 1 experienced erosional behavior (Figure 3.4f, Figure 3.6b). On the other hand, during the period between June 2007 and October 2007, an ebb flow greater than 4,000 m³/s was observed (Figure 3.9), but depositional behavior was noticed in this sector (Figure 3.4g, Figure 3.7a). Therefore, a clear correlation was not found.

3.5 Discussion

The sheltered conditions required for ports are the reason why many ports worldwide are located in estuaries. However, this characteristic is also related to a common issue: the process of siltation (Van Rijn, 2016). Sediments are transported by the flow and deposited when the flow loses strength (Winterwerp, 2005). Understanding the sedimentation patterns of ports is fundamental to optimize the maintenance of channels and waterways, and requires a thorough understanding of local morphology and hydrodynamics since different mechanisms play a role in each environment (Winterwerp, 2005). This study evaluated the sedimentation processes in the access channel of the Port of Rio Grande by analyzing and comparing Digital Elevation Models (DEMs) generated through bathymetric surveys. The study period considered is from 2005 to 2009, before the extension and channel deepening performed in 2009/2010 (Silva et al., 2015; António et al., 2020). To support the analysis of bed evolution over time, discharge data of the lagoon were also considered.

3.5.1 Analysis over time

The temporal analysis consisted of an assessment of how the channel behaved over time and whether there was a correlation between deposition/erosion and discharge (flood or ebb flow) during the period.

Five periods of time were analyzed for Sectors 4 and 5, based on available data (Figure 3.4c,e,h,i,j). Net sedimentation rates were higher from January 2006 to June 2006 (Figure 3.4e), October 2007 to March 2008 (Figure 3.4h), and January 2009 to May 2009 (Figure 3.4j). The analysis of discharge data of the same periods indicated low ebb flow and even flood flow from January 2006 to August 2006 and January 2009 and May 2009 (Figure 3.9).

From October 2007 to March 2008, there was a gradual reduction in ebb flow (Figure 3.9), providing enough time for sediment deposition as the flow gradually lost strength and its capacity to carry sediments (Winterwerp, 2005). Bastos da Silva et al. (2023) analyzed the bottom evolution in other parts of this environment and found a strong depositional process in the area during this period.

On the other hand, from March 2005 to January 2006 (Figure 3.4c) and March 2008 to January 2009 (Figure 3.4j), only slight deposition or erosion occurred in Sectors 4 and 5, and an abrupt reduction of ebb flow was observed in discharge data (Figure 3.9). Small net sedimentation rates and stability conditions were also noticed in other areas of the channel in these periods of time (Bastos da Silva et al., 2023). The difference between these results (slight deposition/erosion) and the behavior observed in the period between October 2007 and May 2008 may be related to the fact that in this last period (Oct 2007 – May 2008), the reduction of ebb flow was gradual (Figure 3.9). This gradual reduction gave time for the sediments to settle, as the flow gradually lost its ability to carry sediment.

Although bathymetric data were not available for the study area of this paper, Bastos da Silva et al. (2023) found an intense erosion in the bottom from May 2007 to October 2007. This behavior may have occurred in other internal regions of the channel, resulting in greater depths. As the flow loses strength, the equilibrium depths were re-established throughout the region, leading to a large amount of sediment being settled on the bottom.

The analysis of Sector 3 also included five different time periods (Figure 3.4b,c,h,i,j) considering the unavailability of discharge data between March and June of 2005 (Figure 3.4a). The highest net sedimentation rates were observed from October 2007 to March 2008 and from January 2009 to May 2009 (Figure 3.4h,j). There was a gradual decrease in ebb flow from October 2007 to March 2008, and only a low ebb flow was observed from January 2009 to May 2009 (Figure 3.9).

An erosional state was observed in Sector 3 from June 2005 to January 2006 (Figure 3.4b), which may have strongly influenced the observed behavior from March 2005 to January 2006 (Figure 3.4c). During the last months of these periods (September 2005 – November 2005), strong ebb flow was recorded in the Patos Lagoon estuary (Figure 3.9). Furthermore, small net sedimentation rates and erosion were also observed in Sector 3 from March 2008 to January 2009 (Figure 3.4i). This period was characterized by an intense ebb flow, which peaked at more than 6,000

m^3/s in November 2008 (Figure 3.9). The flood flow recorded in December 2008 (Figure 3.9) may have contributed to the slight deposition that occurred in Sector 3.

The temporal analysis of Sector 2 demonstrated a highly dynamic behavior. The six rectangular areas comprising Sector 2 (2A - 2F) did not exhibit consistent behavior when subjected to the same flow conditions, as described in the results section. However, the temporal analysis indicated that areas 2E and 2F tended to behave similarly to areas 3A and 3B, particularly in relation to the time periods analyzed (Figure 3.4a,b,c,h,i,j).

The 2E area is situated at the boundary of the west jetty extension (Figure 3.1). The 2A, 2B, 2C, and 2D areas did not show a behavior (Figure 3.4b,c,d,g,i,j) directly correlated to the discharge levels (Figure 3.9). This observation also applies to Sector 1, where the deposition process was dominant over time, but no direct correlation with discharge data was found.

The hydrodynamics of Patos Lagoon are influenced by wind and river discharge from the hydrographic basin (Moller and Castaing, 1999; Moller et al., 2001). The discharge levels in the inlet (Figure 3.9) can be attributed to the combined effect of these factors. The residual flow is directed towards the ocean and is influenced by both the river basin's contribution and the prevalence of northeast winds (Möller and Castaing, 1999), as observed in the discharge data analysis for the study period (Figure 3.9). Möller and Fernandes (2010) confirmed the existence of a negative correlation between river discharge from the hydrographic basin and salinity in the Patos Lagoon estuary.

According to the results, a correlation was found between erosion/deposition processes and the discharge data. Higher ebb flow levels induced an erosion process or stable conditions in the bed channel, in the rectangles covered by sectors 5, 4, 3, and areas 2E and 2F (Figure 3.4, Figure 3.9). This finding is consistent with the results observed by Bastos da Silva et al. (2023), who analyzed other parts of the same channel over a period of 17 years.

The flow towards the ocean is increased during ebb conditions, which leads to a reduction in salinity levels in the estuary (Möller and Fernandes, 2010; António et al., 2020; Franzen et al., 2023). Möller et al. (2001) stated that the river input plays a primary role during the annual flood peak in late austral winter, and freshwater discharge controls the dynamics of the lagoon during this period. Fine suspended sediment particles cannot settle down in the lagoon during these conditions and are transported towards the coastal area (Möller et al., 2001).

On the other hand, during low ebb flow or flood flow, deposition was predominant in these regions (Figure 3.4, Figure 3.9). The predominance of deposition was also observed in the transition states between intense ebb and flood flow, with emphasis on the period between October 2007 and March 2008. When the ebb flow lost strength, favorable conditions were created for the sediments to settle on the bottom. Additionally, the quiescent conditions and higher salinity levels during flood flow (António et al., 2020) can lead to the predominance of deposition.

Ivanoff et al. (2020) analyzed recent sedimentation in Patos Lagoon using ^{210}Pb and ^{137}Cs and found that sedimentation rates strongly increased during El Niño years in the south of the lagoon, in the vicinity of the Camaquã River and São Gonçalo channel. However, it appears that this behavior may not be observed in the estuarine area of Patos Lagoon. Since high discharge is observed in the estuary during El Niño years (Fernandes et al., 2002; Möller et al., 2001; António et al., 2020), it is expected that sedimentation rates are lower during these periods based on the data analyzed in the results. This is because the intense ebb flow prevents sediment deposition in the channel bed as the sediments are transported towards the ocean by the flow. Ávila and Gallo (2021) also concluded that negative discharge anomalies promote sedimentation conditions in the Magdalena River delta (Colombia), while positive discharge anomalies promote erosion stages. Pontee et al. (2004) identified that seasonal increases in freshwater discharge were capable of reducing siltation rates in some parts of the Humber Estuary in northern England.

3.5.2 Spatial patterns

The analysis of bathymetric surveys of the entire channel enabled the identification of some characteristics of the channel. Three areas showed depths greater than 16 m: the west margin of rectangles 4C, 4D, and 4E; the area between the central parts of rectangles 3F and 3G; and the mouth of the inlet covered by rectangles 2C and 2D (Figure 3.3). Although the channel was dredged to reach a depth of 14 m, the results indicated that the hydrodynamic conditions in these regions were capable of maintaining depths around 16 m.

The west margin of the rectangles 4C, 4D, and 4E presents a concave shape and this configuration can contribute to the acceleration of the flow in this region, maintaining great depths (Earle, 2015; Paiva et al., 2020). As previously described, Long and Paim (1987) also commented on the erosive trend in this meander of the channel.

Nogueira (2006) and Silva et al. (2015) used numeric models to analyze the hydrodynamic of the region during ebb flow. Both studies identify that the current velocities are intensified in the mouth of the inlet and in the region between the central areas of the rectangles 3F and 3G. These hydrodynamics characteristics explain the configuration of the channel in these areas.

The central region between the jetties covered by rectangles 2E and 2F exhibited depths mostly below 14 m (Figure 3.3). Furthermore, the analysis of the channel's morphologic evolution revealed a tendency for sediment to accumulate in this area, as evidenced by Figure 3.6a, Figure 3.7b, and Figure 3.8a,b. Due to the interaction of multiple processes, sediment dynamics in this region are highly complex.

Based on the data from Nogueira (2006) and Silva et al. (2015), the region experiences an intensification of currents during ebb flow (which predominates in the Patos Lagoon inlet) that could contribute to erosion. However, this phenomenon was not observed during many of the periods analyzed in this study. Antiqueira and Calliari (2005) studied the hydrodynamics of the region while taking sediment distribution into consideration. They found that the area between jetties exhibits moderate to high hydrodynamic conditions due to the combination of marine and freshwater systems. As a result, sediment trapping between jetties may be mainly influenced by not only freshwater discharge but also saltwater intrusion.

The asymmetry of jetty length and dredging activity promote lateral flow stratification in the Patos Lagoon mouth, where ebb occurs near the west jetty and flood near the east jetty (Fernandes et al., 2005; António et al., 2020). This fact could explain another characteristic observed in the region between the jetties. During erosional stages, such as from March 2005 to January 2006 and from June 2005 to January 2006, most sediments were removed from the west margin of rectangles 2E and 2F (Figure 3.5b,c). Bathymetric data from October 2007 (Figure 3.3c), taken after a period of intense ebb flow (Figure 3.9), also exhibited the same configuration, with greater depths next to the west margin.

The analysis of Sector 1 morphology revealed that smaller depths were located in the northwestern portion (rectangle 1C) and depths increased in the southeast direction (rectangle 1A) (Figure 3.3). The sediment dynamics in this area vary significantly in both time and space, and no correlation was found with lagoon discharge. The same applies to rectangles 2A, 2B, 2C, and 2D, which are located outside the jetty limits, in the inner continental shelf (marine domain). In these areas, other agents, such as waves and coastal currents, may control deposition/erosion processes. Therefore, further data and analysis are necessary to better understand the behavior of the channel in the marine domain.

3.6 Conclusions

The sediment patterns in the access channel of the Patos Lagoon estuary using bathymetric data from 2005 to 2009 were investigated in this study. We considered the channel's configuration prior to the channel deepening and the modernization of the jetties made in 2009 and 2010. Bathymetric surveys provided by the Port Authority (Portos RS) were used to create Digital Elevation Models, and we also analyzed the discharge data of Patos Lagoon.

Discharge appears to be an important factor in controlling siltation in the inner channel (Sectors 5, 4, 3, and rectangles 2F and 2E), as high ebb flow levels were associated with minor net sedimentation rates, while low ebb flow or flood flow was linked to major net sedimentation rates. Bastos da Silva et al. (2023) observed this behavior for other sections of the channel as well. However, this pattern was not observed in rectangles 2A-2D and Sector 1, which are located in the marine domain. No clear correlation between accretion/erosion patterns and discharge levels was found for these areas, which was expected considering other agents, such as waves and coastal currents, also play a key role in the marine domain.

The analysis of bathymetric surveys has enabled the identification of channel characteristics. The mouth of the inlet (2C, 2D), the concave margin of rectangles 4C, 4D, and 4E, and the region between the central points of rectangles 3F and 3G tended to have greater depths than the adjacent areas (>16 m).

In the inner channel, sediment trapping was found to be effective in the region between the jetties, which can be attributed to the moderate hydrodynamic conditions previously identified in this area, as well as to the saltwater intrusion. Minor depths were observed in the east margin of the inner channel. In sector 4, sediment tended to accumulate in the east margin (convex form), while the concave margin remained relatively stable most of the time. In sector 1, deposition was predominant in all periods analyzed.

Understanding the morphological evolution and characteristics of the channels is essential for port design and minimizing siltation. Retrospective in situ data provides important insights into the tendencies and characteristics of the channel, as different factors play a role in each environment. Although Bastos da Silva et al. (2023) used bathymetric data series to analyze the morphological evolution of the channel, the specific portion of the channel examined in this paper has not been studied previously.

Acknowledgments

The authors would like to express their gratitude to the Rio Grande Port Authority (Portos RS), especially Sávio Novo and Mario Dutra, for providing the data and information necessary to support this study. We would like to thank Leo Afraneo Hartmann for his invaluable contributions to scientific writing. Additionally, we acknowledge Elaine Siqueira Goulart for her assistance in providing clarification regarding the bathymetric data and Osmar Olinto Möller Junior for answering our questions regarding the hydrological data. The first author (M.J.B.d.S.) acknowledges the National Council for Scientific and Technological Development (CNPq - Brazil) for sponsoring their work.

Funding

This work was supported by the CNPq (the National Council for Scientific and Technological Development - Brazil).

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CAPÍTULO 4

ARTIGO 3

SILTATION IN THE NAVIGATION CHANNEL OF PATOS LAGOON ESTUARY, BRAZIL, CONSIDERING THE CURRENT CONFIGURATION OF THE JETTIES AND THE CHANNEL

Submetido ao periódico Geo-Marine Letters (ANEXO C).

4. SILTATION IN THE NAVIGATION CHANNEL OF PATOS LAGOON ESTUARY, BRAZIL, CONSIDERING THE CURRENT CONFIGURATION OF THE JETTIES AND THE CHANNEL

Marine Jusiane Bastos da Silva[a,*], José Antonio Scotti Fontoura[b], Iran Carlos Stalliviere Correa[a], and Christian Garcia Serpa[b]

[a]Federal University of Rio Grande do Sul, Campus do Vale, Av. Bento Gonçalves, 7712 - Agronomia, Porto Alegre, Rio Grande do Sul, 91540-000; marinebastos@yahoo.com.br; iran.correa@ufrgs.br

[b]Federal University of Rio Grande, Campus Carreiros, Av. Itália, s/n - km 8 - Carreiros, Rio Grande, Rio Grande do Sul; scottifontoura@gmail.com; christianserpa@yahoo.com.br

*Corresponding author: marinebastos@yahoo.com.br

Abstract

The sediment dynamics, mainly the deposition processes, is one of the most important aspects concerning ports. Understanding sediment patterns is vital for port management since it supports the search for strategies that minimize siltation or promote more sustainable management. This study aims to assess the morphological characteristics and siltation patterns of the access channel to the Patos Lagoon estuary, after the modifications made in the jetties geometry and in the channel configuration in the late 2000s. The Port of Rio Grande, one of the largest in Brazil, is located on the west margin of the inlet. Bathymetric data provided by the Port Authority from 2015 to 2020 were used to generate digital elevation models and then assess the net sedimentation rates and the evolution of the channel bottom over time. Results indicate a significant variability of net sedimentation rates. The volume of sediment deposited on the channel bottom in approximately one year was roughly 2.5 times greater than that deposited in 2 years and 3 months. The entrance area, covered by rectangles 3B-4C (which represented 34% of the study area), was responsible for about 50% of the net sedimentation volume in both analyzed periods. The area between jetties (3E-4C) showed major net sedimentation rates in both periods. The analysis of the bathymetric data series was effective in evaluating important morphological characteristics of the channel, and it was possible to identify aspects of siltation patterns and obtain yielded unprecedented results.

Keywords: siltation, navigation channel, Patos Lagoon, sediment, sedimentation.

4.1 Introduction

Marine transport is continuously evolving to meet the demands of international commerce (PIANC, 2015). Since many ports are located in estuaries, primarily due to their sheltered waters, the estuarine environments have been modified to enable the navigation of larger vessels (van Maren et al., 2015; Prumm and Iglesias, 2016).

These modifications generally involve channel deepening, land reclamation, and the construction of coastal engineering structures such as jetties, quays, and breakwaters (van Maren et al., 2015; Franzen et al., 2021; Zhang et al., 2022). These anthropogenic alterations can have several impacts on hydrodynamics, sediment dynamics, saltwater intrusion, estuarine circulation, and other aspects (António et al., 2020), significantly affecting the behavior of the environment.

The Patos Lagoon estuary, situated on the southern Brazilian coast, is an example of an estuarine environment that has been modified by human activity. In the early 1900s, two jetties were constructed at the inlet to ensure safe navigation, making it one of the largest coastal engineering works performed in Brazil (Cunha and Calliari, 2009). This construction has had the most significant and irreversible effect on the estuarine circulation patterns in the Patos Lagoon estuary (Möller and Fernandes, 2010). The configuration of the jetties remained unchanged until 2009 when both jetties were extended towards the ocean, and a capital dredging was performed to deepen the channel that connects the Atlantic Ocean to the Patos Lagoon (Silva et al., 2015; António et al., 2020). These modifications were carried out to support the development of the Port of Rio Grande, which is one of the largest Brazilian ports, located on the west margin of the estuarine mouth.

Sediment dynamics is crucial to ports since it can cause siltation and restrict navigation. Many ports worldwide experience significant siltation (Winterwerp, 2005), requiring strategies to prevent sediment deposition or remove sediments, such as maintenance dredging. Understanding sedimentation patterns is essential to support port management and develop sustainable strategies to minimize environmental negative impacts.

This study aims to assess the configuration and sedimentation patterns of the Port of Rio Grande channel after the modifications made in the late 2000s, using bathymetric data provided by the Port Authority from 2015 to 2020. This study identified significant aspects of siltation patterns and yielded unprecedented results.

4.2 Study area

4.2.1 The Patos Lagoon Estuary

The Patos Lagoon is the world's largest choked lagoon (Kjerfve, 1986) located in the southernmost region of the Brazilian coast, extending 250 km with a main axis oriented in the northeast-southwest (NE-SW) direction (Möller et al., 2001). It receives water from a 201,626 km^2 drainage basin and from the Mirim Lagoon, which is connected through the São Gonçalo Channel (Asmus, 1997) (Figure 4.1). The estuarine area covers the southern part of the Patos Lagoon, where a single channel links the lagoon to the South Atlantic Ocean (Garcia, 1997) (Figure 4.1).

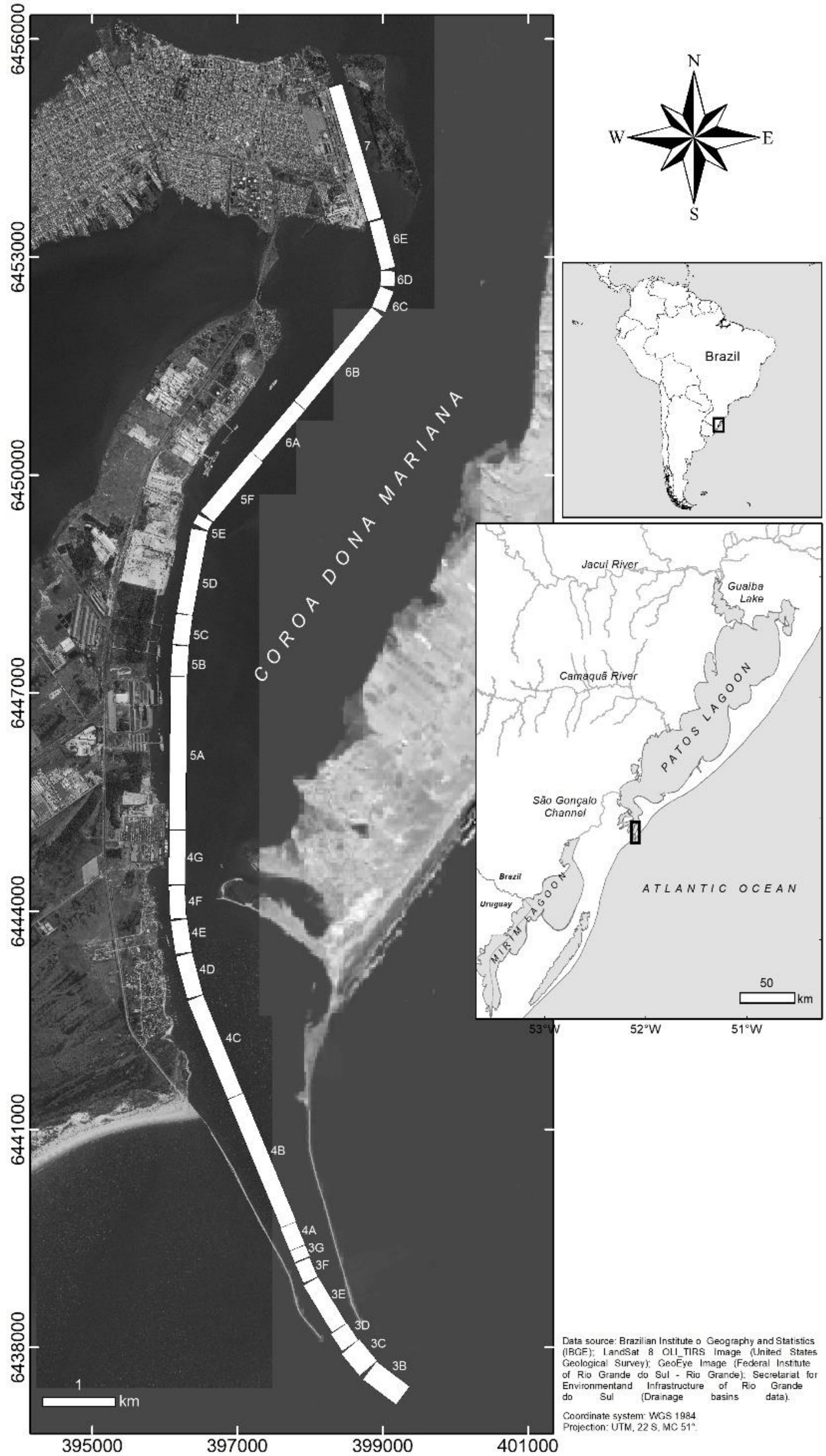

Figure 4.1: Study area. Sectors were divided into rectangular areas - Sector 3 (3B-3G), Sector 4 (4A-4G), Sector 5 (5A-5F), Sector 6 (6A-6E), and Sector 7.

Tides in the Patos Lagoon are predominantly mixed-diurnal, with a mean amplitude of 0.47 m (Garcia, 1997). However, the tidal influence is of secondary importance (Möller et al., 2009; Möller and Fernandes, 2010) because the estuary is micro-tidal (Fernandes et al., 2005). Wind action and freshwater discharge control the hydrodynamics (Möller et al., 2001; Möller et al., 2009; Möller and Fernandes, 2010). During low to moderate river discharge periods, the wind drives the circulation, while river input plays a crucial role during the annual flood peak in late austral winter (Möller et al., 2001).

The dominant wind regime coincides with the NE-SW orientation of the lagoon's main axis (Möller et al., 2001). Northeasterly winds (NE) occur 22% of the year with a mean velocity of 3.6-5.1 m/s, while southwesterly winds (SW) occur 12% of the year with a mean velocity of 5.4-8.2 m/s (Garcia, 1997). SW winds become more significant during austral autumn and winter as they are associated with frontal systems (Möller et al., 2001). Seaward flow (ebb) in the estuary is associated with NE winds, while landward flow (flood) is related to the action of the SW winds (Möller et al., 2001; Fernandes et al., 2002).

Below-average river discharge (2,400 m^3/s) occurs in late spring and summer, while above-average river discharge occurs in winter and early spring (Möller and Fernandes, 2010). River discharge far exceeds average values during El Niño events (Garcia, 1997). The predominance of seaward flow was observed during an El Niño event because the increased discharge at the top of the lagoon led to an intensification in outflow when combined with wind behavior (Fernandes et al., 2002).

A negative correlation between river discharge and salinity levels is observed in the Patos Lagoon estuary, and salinity shows a seasonal pattern (Möller and Fernandes, 2010). Higher salinity levels are observed in late spring and summer, while lower salinity levels are observed in winter, due to increased river discharge (Möller and Fernandes, 2010).

The high level of precipitation in the drainage basin results in a significant fluvial input of fine sediments (silt and clay) in the Patos Lagoon estuary (Calliari et al., 2008). The sediment distribution in the estuary bed is related to depth and hydrodynamic energy levels: silty clay sediments dominate deep channels, while sands are predominant in shallow areas (Calliari, 1997; Calliari et al., 2008). Sandy bottoms are also found in channels where high hydrodynamic energy is observed (Antiqueira and Calliari, 2005; Calliari et al., 2008).

4.2.2 Channel characteristics

A single channel links Patos Lagoon to the Atlantic Ocean (Garcia, 1997), and this channel is also the only maritime access to the Port of Rio Grande infrastructure, which is mainly situated along the west margin of the Patos Lagoon inlet. Other ports, such as the Port of Pelotas and Port of Porto Alegre, are also located in the Patos Lagoon.

The construction of two converging jetties at the mouth of Patos Lagoon aimed to stabilize the inlet and promote the acceleration of the flow towards the ocean, flushing sediments out and allowing vessels with drafts larger than 3 m to access (Möller and Fernandes, 2010). The original configuration of the jetties had a southeasterly orientation, and the west jetty (4,012 m) was shorter than the east jetty (4,250 m) (Cunha and Calliari, 2009). This configuration remained unchanged until 2009 when the length of the jetties was extended towards the ocean to enable channel deepening (Silva et al., 2015). The modernization work was expected to promote natural auto-dredging in the system (Silva et al., 2015).

In the new configuration, the Port Authority divided the access channel into seven sectors (in this study, these sectors are named 1, 2, 3, 4, 5, 6, and 7). Due to the bathymetric data coverage area, sectors 1, 2, and part of sector 3 were not analyzed in this paper. The methodology required that each sector be divided into rectangular areas, as will be explained later. The sector number followed by a letter names each rectangular area (Figure 4.1). Currently, the depth attained is 18 m in sectors 1 to 3, 16 m in sectors 4 and 5, and 10.5 m in sectors 6 and 7 (Porto Novo basin and its access channel). The depth gradually reduces in the 4A area, from 18 m to 16 m (ramp shape).

4.3 Methodology

We used four bathymetric surveys provided by the Port Authority (Portos RS) to analyze the morphological evolution of the access channel to the Patos Lagoon. The bathymetric data were acquired in the following periods: (i) November 2015; (ii) February 2018; (iii) January 2020 (Sectors 2 and 3); September 2019 (Sectors 4 and 5); November 2019 (Sectors 6 and 7); (iv) September 2020. The bathymetric data from September 2019, November 2019, and January 2020 were measured after dredging work in each sector.

Digital elevation models (DEMs) were generated using the bathymetric data and by applying the Kriging method in the software Surfer. We used the methodology proposed and applied by Bastos da Silva et al. (2023) to investigate the morphological evolution of channels based on bathymetric data.

Each sector of the channel was divided into rectangular areas, which were mainly arranged according to the orientation of the channel's main axis (Table 4.1). When the orientation changed, a new rectangular area was created. Each rectangle and its bathymetric dataset were rotated around a fixed vertex so that the base is horizontal. This procedure aimed to obtain a better performance of the Kriging method, creating grids where columns are parallel to the main axis and rows are perpendicular to the main axis. After generating the DEM for each bathymetric survey of each rectangular area, the grid was rotated back to the original position. Bastos da Silva et al. (2023) explained this procedure. Since the study area was divided into 25 rectangles (Figure 4.1) and four bathymetric surveys were available for each sector, we generated 100 DEMs.

We subtracted the older DEM (used as the reference) from the more recent DEM of each rectangle to identify the accretion/erosion/net volumes that occurred in each period through Surfer software. Volumes above the reference were considered positive/accretion and volumes below the reference were considered negative/erosion.

This study analyzed two periods: from November 2015 to February 2018, and from 2019/2020 (it varies according to the sector) to September 2020. This procedure was applied because the channel was dredged in the period between October 2018 to 2019/2020 (it varies according to the sector). Based on the dredging records of the Port Authority, no other dredging work occurred from 2015 to 2020. Therefore, we expected that only natural morphological variations were analyzed. Before this period, dredging work was carried out in 2013/2014 to attain 14.5 m depth in sectors 2, 3, 4, and 5 to 10.5 m depth in sectors 6 and 7.

The net sedimentation rates for each rectangular area and each period were estimated by dividing the net volume by the elapsed time between bathymetric surveys and by the planar area of the rectangle. Positive values indicated the predominance of deposition and negative values showed the predominance of erosion.

Table 4.1: UTM coordinates of the vertices of each rectangular area. WGS 1984, UTM, 22S, MC 51°.

Rectangle	Coord. (m)	Vertex 1	Vertex 2	Vertex 3	Vertex 4
3B	E	399183.0392	399369.514	398914.17	398727.6952
	N	6437213.5093	6437461.1525	6437804.0255	6437556.3823
3C	E	398681.2274	398925.6337	398673.8929	398429.4867
	N	6437609.1312	6437815.6877	6438113.5578	6437907.0013
3D	E	398444.3194	398667.5237	398509.9764	398286.7722
	N	6437950.5648	6438102.4854	6438333.9565	6438182.0359
3E	E	398300.0121	398504.7052	398113.1343	397908.4413
	N	6438205.4735	6438330.7762	6438970.4419	6438845.1392
3F	E	397905.8444	398108.8308	397997.0063	397794.0199
	N	6438885.3419	6438970.1742	6439237.7472	6439152.9148
3G	E	397784.3584	397997.8097	397934.4919	397721.0406
	N	6439166.0269	6439251.6922	6439409.4606	6439323.7953
4A	E	397721.5194	397933.0479	397799.548	397588.0195
	N	6439326.5621	6439416.8709	6439729.5652	6439639.2565
4B	E	397597.1073	397809.5942	397078.561	396866.074
	N	6439645.2945	6439733.3247	6441497.8899	6441409.8597
4C	E	396864.4756	397077.5117	396527.2015	396314.1654
	N	6441411.8548	6441498.5475	6442850.8636	6442764.1709
4D	E	396305.6895	396527.8986	396373.0575	396150.8484
	N	6442796.0626	6442855.4183	6443435.0943	6443375.7386
4E	E	396145.0183	396372.7083	396307.6776	396079.9876
	N	6443408.4954	6443441.0108	6443896.3909	6443863.8755
4F	E	396076.5857	396296.291	396272.4916	396052.7862
	N	6443892.1097	6443903.4921	6444362.876	6444351.4937
4G	E	396051.8722	396281.862	396288.919	396058.9292
	N	6444367.143	6444364.9789	6445114.9457	6445117.1098
5A	E	396059.319	396289.3088	396309.0686	396079.0788
	N	6445127.1996	6445125.0354	6447224.9424	6447227.1066
5B	E	396078.1041	396307.6391	396334.3343	396104.7994
	N	6447242.9188	6447228.3	6447647.4508	6447662.0696
5C	E	396105.8087	396334.1314	396384.7616	396156.4389
	N	6447678.4701	6447650.744	6448067.6812	6448095.4072
5D	E	396158.7955	396385.2952	396590.3761	396363.8764
	N	6448108.4387	6448068.4653	6449230.5074	6449270.4808
5E	E	396389.9287	396594.1844	396658.544	396454.2884
	N	6449337.9778	6449232.2441	6449356.5736	6449462.3073
5F	E	396493.2933	396669.7989	397355.829	397179.3234
	N	6449502.2759	6449354.8115	6450175.9465	6450323.4109
6A	E	397185.3536	397337.9214	397932.7828	397780.215
	N	6450321.3411	6450192.0233	6450893.8352	6451023.1529
6B	E	397779.1387	397933.0015	398999.9159	398846.0531
	N	6451029.0702	6450901.296	6452186.0503	6452313.8245
6C	E	398849.047	399033.8592	399152.3552	398967.543
	N	6452317.2177	6452240.7687	6452527.2275	6452603.6766
6D	E	398963.9005	399163.6761	399173.6214	398973.8458
	N	6452607.0415	6452597.5698	6452807.3342	6452816.8059
6E	E	398981.6885	399175.5278	399008.0513	398814.212
	N	6452816.6073	6452865.8651	6453524.9187	6453475.6609
7	E	398795.9556	398987.7444	398443.2406	398251.4518
	N	6453490.148	6453546.8672	6455388.0395	6455331.3204

Maps were generated to analyze the regions where sediment tends to be trapped in each rectangular area. These maps were created by subtracting the older digital elevation model (DEM) from the more recent one. Since grids of each area have the same dimensions and grid size (10 m), we compared exactly the same points in this operation. Positive values indicated deposition and were represented using shades of red on the map. Negative values indicated erosion and were represented using shades of blue. Variations in depth between ±0.5 m were considered negligible, considering the estimated precision required for the bathymetric data. These points, which had negligible variations, were represented in red or blue with some transparency. This procedure is similar to the technique applied by Bastos da Silva et al. (2023).

4.4 Results

4.4.1 Channel characteristics

Although each sector of the channel is dredged to achieve the depths previously described, the bed is reshaped over time due to hydrodynamics and sediment transport. We analyzed the characteristics of the channel by examining the bathymetric surveys provided by Portos RS (Figure 4.2).

Dredging work was carried out in sectors 2, 3, 4, and 5 to attain a depth of 14.5 m and lasted until February 2014. Bathymetric surveys from November 2015 (Figure 4.2a) and February 2018 (Figure 4.2b) show the morphology of the channel after this activity. The analysis of both surveys allowed the identification of deep areas (16-18 m and 18-22 m classes): (I) in the concave (west) margin of sector 5 (mainly in the areas adjacent to rectangles 5B-5F), (II) in the area from 4D to the central zone of rectangle 5A, and (III) in the central area between the two jetties (at the mouth of the inlet, 3D-3E).

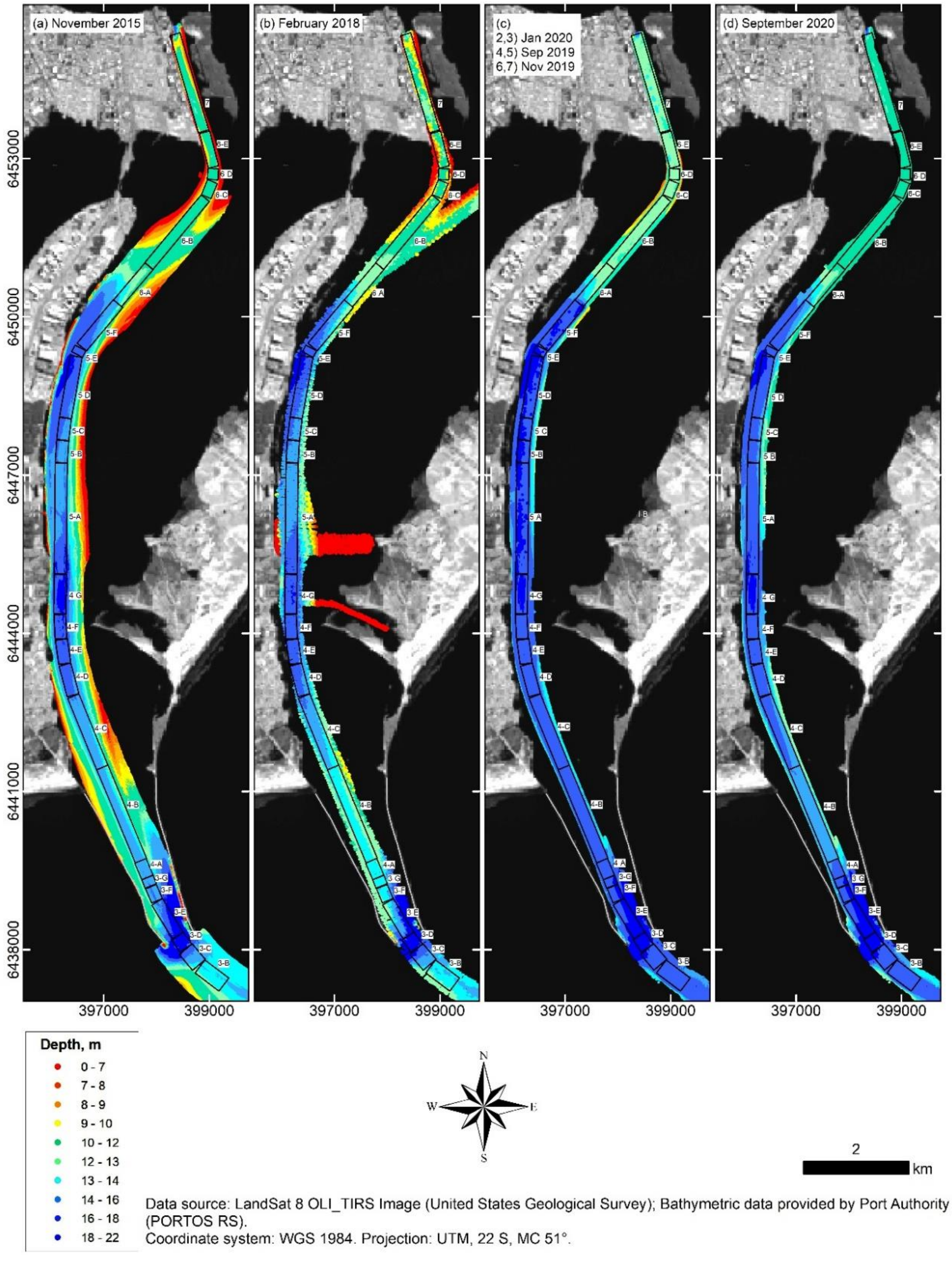

Figure 4.2: Bathymetric surveys provided by Port Authority (PORTOS RS).

We observed that the concave (west) margin of sector 5 exhibited greater depths than the convex (east) margin (Figure 4.2a,b). It was also noticed that the concave margin of sector 6 and the central area of sector 7 (adjacent to the quay) showed larger depths than the surrounding areas (Figure 4.2a,b). The region between the jetties (3F-4C) showed shallower depths when compared to adjacent areas (3E and 4D rectangles) (Figure 4.2a,b).

Analyzing the channel immediately after dredging (Figure 4.2c) and in September 2020 (Figure 4.2d), we were able to identify the channel's evolution over this time. The areas of greater depths previously described (I, II, III) still exhibited the same behavior. Minor depths were also observed in the east margin of most parts of sectors 4 and 5.

There was a clear reduction in depths in the 4B and 4C rectangular areas between September 2019 and September 2020 (Figure 4.2c,d). Depths were around 16-18 m in September 2019 (Figure 4.2c) and were reduced to 14-16 m one year later (Figure 4.2d). This trend was also observed in sectors 6 and 7.

4.4.2 Siltation processes

The investigation into the siltation process was based on the analysis of net sedimentation rates for each rectangular area and maps that demonstrated the evolution of bed morphology over time.

Net sedimentation rates for both periods in each rectangular area showed significant spatial and temporal variation (Figure 4.3). The period between November 2015 and February 2018 (period 1) had lower net sedimentation rates than the period from September 2019 (4, 5)/November 2019 (6, 7)/January 2020 (2, 3) to September 2020 (period 2) (Figure 4.3).

In period 1, deposition was predominant in most rectangular areas, except for 3B, 3C, and 3D (Figure 4.3), which are located outside of the jetties' limits (Figure 4.1). In period 2, deposition prevailed throughout the channel, with a substantially larger magnitude (Figure 4.3). This behavior allows for the identification of where most sediment tends to be trapped in a scenario that favors deposition.

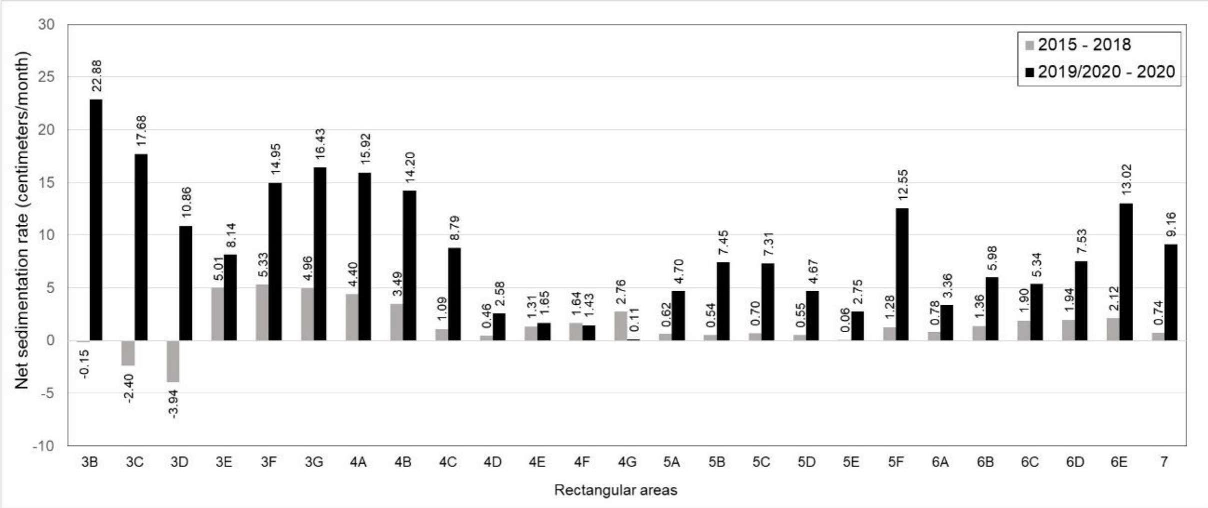

Figure 4.3: Net sedimentation rates in both analyzed periods: (i) from November 2015 to February 2018 (values in grey); (ii) from January 2020 to September 2020 in sectors 2 and 3; from September 2019 to September 2020 in sectors 4 and 5; from November 2019 to September 2020 in sectors 6 and 7 (values in black).

The bed evolution of periods 1 and 2 is depicted in Figure 4.4. It was possible to identify that sedimentation is not uniform in the channel, and certain regions tend to trap more sediments, resulting in reduced depths.

The central area of sector 7 and the concave margin of sector 6 exhibited a quasi-stable condition (indicated by white colors) (Figure 4.4). The northwestern and southeastern parts of sector 7 tended to trap sediments, particularly from November 2019 to September 2020 (Figure 4.4b), when sedimentation was more intense (Figure 4.3). Depositional processes were also evident along the convex margin (west margin) of sector 6 (Figure 4.4a,b). These processes are related to the major net sedimentation rates found in the sector, specifically in the 6E rectangle (Figure 4.3), during both periods.

The transition from the 6A area to the 5F area is characterized by an increase in the volume of trapped sediments (Figure 4.3, Figure 4.4), which is more evident from September 2019 to September 2020 (Figure 4.4b). Sediment deposition in sector 5 was predominant along the east margin (Figure 4.4).

The region extending from the 4D area to the center of the 5A area did not show significant depth variations (Figure 4.3, Figure 4.4), except for a specific area along the east margin of rectangles 4E, 4F, and 4G from November 2015 to February 2018 (Figure 4.4a). However, this pattern changes in the 4C area.

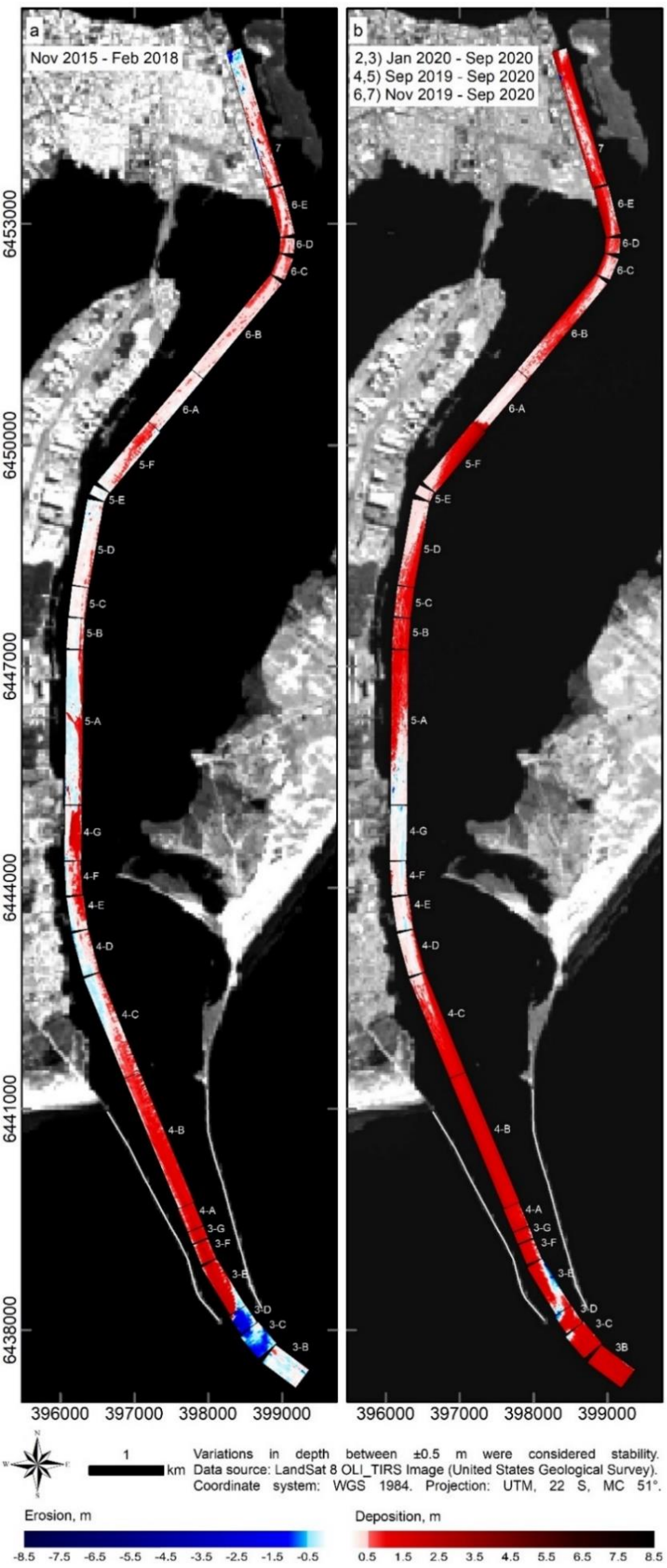

Figure 4.4: Bed evolution (a) from November 2015 to February 2018; (b) from January 2020 to September 2020 in sectors 2 and 3; from September 2019 to September 2020 in sectors 4 and 5; from November 2019 to September 2020 in sectors 6 and 7.

The area between the jetties (from sites 3E to 4C) exhibited an intense deposition process (Figure 4.4), resulting in the highest net sedimentation rates observed in the channel when both periods are analyzed together (Figure 4.3). Nevertheless, the rectangles 3B, 3C, and 3D displayed different behavior during the two analyzed periods. Sediments were predominantly flushed out of these areas from November 2015 to February 2018 (Figure 4.3, Figure 4.4a). However, these areas were responsible for the highest net sedimentation rates observed from January 2020 to September 2020 (Figure 4.3), when conditions favored sediment trapping (Figure 4.4b).

The total net volume in the first period was 1,709,829 m³ (Figure 4.4a) and 4,240,929 m³ in the second period (Figure 4.4b). The entrance area, covered by rectangles from 3B to 4C (Figure 4.4), exhibited a net volume of 848,744 m³ (50% of the total net volume) in the first period, while the same area showed a net volume of 2,175,492 m³ in the second period (51% of the total net volume). The entire study area (encompassing all rectangles) covered 4,398,700 m², with the area between the 3B and 4C rectangles totaling 1,513,300 m², which represents 34% of the total area.

4.5 Discussion

The deposition of sediments on the channel bottom occurs when the flow loses its capacity to transport sediments (Winterwerp, 2005). This process becomes problematic when it reduces the depth of navigation channels, which are the main routes for international cargo transportation. Port maintenance requires strategies to ensure adequate depths (Kirichek et al., 2021). Understanding the spatial distribution of sediments in navigation channels can help develop strategies to reduce siltation and minimize costs.

This study aimed to investigate the siltation patterns in the access channel to the Patos Lagoon estuary, which is also the only maritime route to access the Port of Rio Grande, one of the largest ports in South America. We utilized four bathymetric surveys measured between 2015 and 2020 and digital elevation models to examine the evolution of the channel bottom. The time interval was limited because the geometric configuration of the two jetties at the mouth of the inlet was modified in 2009, which altered the hydrodynamic characteristics (Silva et al., 2015; António et al., 2020). The Port Authority (Portos RS) provided the available bathymetric data for the period after the modernization work.

Bastos da Silva et al. (2023) extensively discussed the siltation processes in sectors 6 and 7. The authors identified that the discharge in the Patos Lagoon inlet appeared to control the magnitude of siltation in the channel, as minor sedimentation rates were observed when the ebb flow was intensified.

The convex margin of sector 6 (Porto Novo access channel), particularly the rectangular area 6E, and sector 7 (Porto Novo basin) were responsible for a significant part of the siltation in the region (Bastos da Silva et al., 2023), which was also observed in this study (Figure 4.3, Figure 4.4). The 6B and 6A areas are situated in a region where the mean ebb flow current is intensified (Franzen et al., 2023), which can contribute to the stability conditions observed in most points, favoring sediment transport.

The transition between sectors 5F and 6A is also the transition between different depths in the channel. Sector 5 was dredged to a depth of 16 m, while sector 6 was dredged to 10.5 m in 2019 (Figure 4.2c). Therefore, it appears that sector 6 has depths close to the equilibrium water depth, as no significant variation in depths was detected in the 6A during the period (Figure 4.4b).

The transition between 5F and 6A areas is also characterized by a reduction in the mean ebb flow velocity, as observed in the results presented by Franzen et al. (2023). The loss of ebb flow strength can contribute to sediment deposition in this area (Winterwerp, 2005) as the bottom tends to reach the equilibrium water depth. Results also suggested that the bottom in Sector 5 was close to the equilibrium in the first observed period, from November 2015 to February 2018 (Figure 4.2a,b, Figure 4.4a), as only a small deposition was detected.

Franzen et al. (2023) indicated the mean current velocity at the bottom during ebb flow dominance in the estuary and it demonstrated low values in the east margin of the channel, near the Coroa Dona Mariana area (Figure 4.1) where small depths are found. The low velocities observed by the authors can be associated with the siltation pattern observed in this location, in the east margin of the area comprised of 4D-5F rectangles (Figure 4.4). Van Rijn (2013) also commented that the bathymetry of the area, specially shoals near the channel, influence the local current pattern and hydrodynamic processes.

The region between the 4D and center of 5A rectangles exhibited low net sedimentation rates (Figure 4.3) and stable conditions in most locations during both observed periods (Figure 4.4a,b), with depths varying ±0.5 m. The bathymetric surveys conducted in 2015 (Figure 4.2a) and 2018 (Figure 4.2b) revealed that these areas typically have greater depths than the surrounding regions. The mean ebb current velocities in these areas are intensified (Franzen et al., 2023), which allows for the maintenance of larger depths and reduces the deposition of sediments (Figure 4.4).

The entrance region (3B-4C, which represents 34% of the entire study area) was responsible for approximately 50% of the total net volume during each period. The area between the 3E and 4C rectangles exhibited significant net sedimentation rates in both periods (Figure 4.3). Although Franzen et al. (2023) demonstrated that the flux is more pronounced in this region during ebb flow (which is predominant in Patos Lagoon), the flow is incapable of removing sediment or preventing deposition in this region. However, the strength of local currents in the mouth of the inlet (rectangles 3C and 3D) was sufficient to naturally maintain depths larger than 18 m and even promote significant erosion in the area, in the period from November 2015 to February 2018 (Figure 4.3, Figure 4.4a).

Silva et al. (2015) also analyzed the hydrodynamic conditions and sediment deposition for the area between the jetties. The authors identified an increase of up to 44% in fine silt deposition along the access channel compared to the previous configuration (before the deepening of the channel and the modification of the jetties). This increase was associated with the decrease in mean velocity observed in the area after the modifications made in 2009 (Silva et al., 2015). Although this information is relevant to improve the discussion, comparisons between the previous and current configurations were not within the scope of our study.

According to van Maren et al. (2015), it is highly likely that channel deepening promotes an increase in suspended sediment concentration due to higher siltation rates and intensification in up-estuary suspended sediment transport due to enhanced salinity-induced estuarine circulation. It is important to note that freshwater discharge higher than 3,000 m³/s blocks saline water intrusion into the Patos Lagoon estuary (Möller et al., 1991; Calliari et al., 2008; Möller and Fernandes, 2010). However, the mean river discharge is 2,400 m³/s (Möller and Fernandes, 2010). Therefore, the strengthening of the flood flow can be associated with the high siltation in the entrance area between jetties (3E-4C), since deep depths are found in that location.

The period between November 2015 and February 2018 (2 years and 3 months) exhibited lower net sedimentation rates compared to the period between the completion of dredging work and September 2020 (Figure 4.3). During the first period, the dredging work had been finished in January 2014, which was approximately 1 year and 9 months prior to the first bathymetric survey (November 2015). Martelo et al.

(2019) reported that rapid siltation occurs in the channel immediately after dredging work is completed, and this behavior was observed in the study area. The net volume during the second period was almost 2.5 times greater than in the first period.

Although hydrodynamic conditions may play a key role and were not analyzed, the large amounts of sediment deposited after dredging have drawn attention to the fact that, even though dredging is the most widely used solution for increasing depths in navigation channels, it does not prevent siltation over time (Bianchini et al., 2019). Rapid siltation can still be observed in the area after dredging (Martelo et al., 2019). Bastos da Silva et al. (2023) conducted a study on the sedimentation processes in the Porto Novo basin and its access channel (sectors 6 and 7 in the Port of Rio Grande) and found that high ebb flow, acting during a certain time interval, can naturally remove sediments in the area. However, in the absence of these erosion-favoring conditions, sediment deposition remains the most common process observed.

Channel siltation can be minimized by increasing the velocity of the dredged channel to keep sediment moving, or by reducing the concentration of suspended sediment reaching the channel to keep the sediment out of the area (Headland et al., 2007). Some strategies with low maintenance costs and limited environmental impact have been analyzed (Bianchini et al., 2019) to propose more sustainable alternatives for sediment management in ports. Although further data can improve the initial analysis shown in this study, important results have been found that can help to understand the siltation patterns in the Port of Rio Grande access channel and serve as a tool to improve sediment management strategies.

4.6 Conclusions

The analysis of bathymetric data and digital elevation models was effective in assessing important morphological characteristics and the siltation patterns of the unique channel that links the Patos Lagoon to the Atlantic Ocean. Results indicate a significant variability of net sedimentation rates. The volume of sediment deposited on the channel bed in approximately one year was roughly 2.5 times greater than that deposited in 2 years and 3 months.

The entrance area, covered by rectangles 3B-4C (which represented 34% of the study area), was responsible for about 50% of the net sedimentation volume in both analyzed periods. There is an association between regions that tend to trap more sediments and the loss of strength by the mean currents during ebb flow (predominant in the Patos Lagoon), according to hydrodynamic studies of the region (Franzen et al., 2023). The area between jetties (from sites 3E to 4C rectangles) showed major net sedimentation rates in both periods.

Further data are necessary to expand the analysis of the channel over a longer time interval. However, the results contribute to understanding the siltation patterns in the channel considering the modern configuration of the jetties and can support the improvement of sediment management.

Acknowledgments

The authors acknowledge the Rio Grande Port Authority (Portos RS), especially Sávio Novo and Mario Dutra, for providing the data and information necessary to support this study. We thank Leo Afraneo Hartmann for his priceless contributions to scientific writing. The first author (M.J.B.d.S.) acknowledges the National Council for Scientific and Technological Development (CNPq - Brazil) for sponsoring their work.

Funding

This work was supported by the CNPq (the National Council for Scientific and Technological Development - Brazil).

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CAPÍTULO 5

CONSIDERAÇÕES FINAIS

5. CONSIDERAÇÕES FINAIS

5.1 Síntese

A análise de dados de levantamentos batimétricos e de dados hidrológicos do canal de acesso ao estuário da Lagoa dos Patos permitiu a identificação de padrões na dinâmica de sedimentos na região, especialmente dos processos de deposição e erosão, tanto espacialmente quanto temporalmente.

A investigação do canal de acesso ao Porto Novo e da bacia do Porto Novo ao longo de 17 anos foi apresentada no artigo 1 (Capítulo 2). A delimitação espacial do artigo se deu pelo fato de que essa região não teve a profundidade de projeto alterada tampouco seu traçado ao longo do tempo. Observou-se que as características do canal e da região ao redor constituem um fator chave para definir os padrões espaciais de sedimentação. A curvatura, a presença de um baixio nas adjacências do canal de acesso ao Porto Novo (Coroa do Boi) e a morfologia anterior às modificações antrópicas foram os principais fatores observados.

As maiores taxas de sedimentação foram observadas na porção noroeste da bacia do Porto Novo e na margem convexa do canal de acesso ao Porto Novo (margem oeste), principalmente no setor 5E, conforme dados apresentados no Capítulo 2. A comparação entre os modelos digitais de elevação gerados a partir do primeiro e do último levantamento batimétrico disponível entre dragagens consecutivas permitiu identificar que as áreas da bacia e do retângulo 5E responderam por valores entre 42,4% e 86,3% do volume líquido positivo detectado em cada período entre dragagens. Portanto, constituem áreas críticas no que diz respeito ao assoreamento. Já a porção sudeste da bacia, a margem côncava do canal de acesso e o setor 5B não apresentaram variações significativas de profundidade ao longo do tempo.

Quanto às condições hidrológicas, observou-se que a vazão na desembocadura pode ser um importante fator de controle na deposição de sedimentos. Destaca-se, no Capítulo 2, o evento ocorrido no ano de 2007, no período entre os meses de junho e outubro, quando mais de 585 mil m³ foram removidos naturalmente do canal (não foram encontradas registros de dragagem nesse setor e nesse periodo). Observou-se que a constância de um fluxo de vazante excedendo 4.000 m³/s ao longo de 5 meses (junho a outubro de 2007) pode ter sido determinante para esse comportamento. Já no periodo subsequente, entre outubro de 2007 e março de 2008, o volume líquido foi positivo de 594,464 m³, indicando uma recuperação natural do sistema sob a ação de um fluxo predominante de vazante de menor intensidade e, também, de fluxo de enchente.

A investigação dos demais trechos do canal na configuração anterior ao apronfundamento, às modificações geométricas e ao prolongamento dos molhes foi analisada no artigo 2 (Capítulo 3). Para concentrar apenas o cenário anterior as modificações citadas, esse artigo limitou-se a investigar dados entre os anos de 2005 e 2009.

As análises apresentadas no Capítulo 3 reforçaram comportamentos indicados no Capítulo 2. A intensidade da descarga pareceu ser um fator importante de controle da deposição na porção interna do canal, correspondente aos setores 5, 4, 3 e retângulos 2F e 2E. Observou-se que fluxos mais intensos de vazante estavam associados com períodos de menores taxas líquidas de sedimentação, enquanto que fluxos de vazante de menor intensidade ou períodos de predominância de fluxo de enchente estavam ligados a períodos com maiores taxas líquidas de sedimentação.

Entretanto, esse padrão não foi observado nos retângulos 2A a 2D e no setor 1, que contemplam a porção do canal localizada no domínio marinho na configuração pretérita (Capítulo 3). Uma marcante mudança de comportamento das taxas líquidas de sedimentação é observada no limite entre os retângulos 2D e 2E, reforçando o comportamento dominado pelo fluxo de enchente/vazante na porção interna e na área abrigada pelos molhes. No setor 1, localizado no domínio marinho na configuração pretérita, observou-se que a deposição de sedimentos é predominante ao longo do tempo.

A análise de dados de levantamentos batimétricos também permitiu a identificação de características morfológicas do canal na sua configuração pretérita (Capítulo 3). A região da desembocadura (abrangida pelos retângulos 2C e 2D), a margem côncava localizada na margem oeste dos retângulos 4C, 4D e 4E e, também, a região entre as zonas centrais dos retângulos 3F e 3G apresentaram profundidades naturais superiores às áreas adjacentes (>16 m). Menores profundidades foram observadas na margem leste do canal interno, que possui uma forma convexa e está adjacente à Coroa Dona Mariana, uma região de baixio. Comportamento semelhante também foi observado na região adjacente à Coroa do Boi, conforme apresentado no Capítulo 2.

No Capítulo 4, buscou-se analisar a configuração atual do canal de acesso ao estuário da Lagoa dos Patos. Embora ainda poucos dados de levantamentos batimétricos estejam disponíveis para o atual cenário, já foi possível detectar uma significativa variabilidade nas taxas líquidas de sedimentação. O volume de sedimentos depositado no canal em aproximadamente 1 ano (variações para mais ou para menos dependendo do trecho considerado) foi 2,5 vezes maior que o volume depositado em 2 anos e 3 meses. Tais resultados podem estar relacionados a fatores como: agentes hidrodinâmicos, profundidade atingida pelas dragagens anteriores a cada período, tempo decorrido entre os levantamentos analisados e a última dragagem realizada.

Na configuração atual (Capítulo 4), a análise foi limitada ao canal interno e à região imediatamente adjacente à desembocadura. Observou-se que a área de acesso ao canal, compreendida pelos retângulos 3B a 4C, foi responsável por aproximadamente 50% do volume líquido de sedimentos depositados em ambos períodos analisados. Isso significa que aproximadamente metade do volume líquido depositado em toda a região de estudo foi concentrada nesa região (3B-4C), que compreende apenas 34% da área de estudo deste artigo.

A área entre os molhes, compreendida entre os retângulos 3E e 4C, apresentou as maiores taxas líquidas de sedimentação em ambos períodos analisados Capítulo 4. Ressalta-se que os dados referentes ao período entre 2015 e 2018 mostram que há uma mudança de comportamento nas taxas líquidas de sedimentação no limite entre os retângulos 3E e 3D. Esse limite marca a linha que separa a zona abrigada pelos molhes na configuração atual e o domínio marinho. Embora haja necessidade de uma análise de um espaço temporal mais longo, esse comportamento pode vir a reforçar aquele analisado no Capítulo 3, no qual se identificou a mudança de comportamento das taxas de sedimentação justamente na zona limite abrigada pelos molhes na configuração pretérita.

A partir do exposto, reforça-se que o presente trabalho é inédito no que diz respeito ao estudo dos processos sedimentares no canal de acesso à Lagoa dos Patos utilizando dados de levantamentos batimétricos. A metodologia empregada permitiu acessar importantes características do canal, não apresentadas previamente na literatura.

Considera-se, com base no que foi apresentado, que a investigação de dados pretéritos, assim como o monitoramento de longo prazo são fulcrais para o ampliar o que se sabe sobre ambiente costeiro em análise. A busca pelo desenvolvimento sustentável parte de um pressuposto: o de que se conhece o ambiente. Portanto, torna-se evidente que são indispensáveis ações de monitoramento *in situ* e a observação contínua do ambiente, ou seja, é necessário monitorá-lo e observá-lo para, então, conhecê-lo.

5.2 Recomendações para trabalhos futuros

(1) Para maior celeridade no estudo das taxas de sedimentação, recomenda-se o desenvolvimento de uma ferramenta que permita automatizar e aprimorar o método utilizado, dividindo a área de interesse em retângulos e permitindo a utilização de diferentes interpoladores, por exemplo;

(2) É relevante estender a análise da configuração atual do canal com base em levantamentos batimétricos, à medida que esses dados estiverem disponíveis;

(3) Para ampliar o conhecimento da porção do canal em domínio marinho, é relevante expandir a análise com base em levantamentos batimétricos nessa região e investigar os agentes hidrodinâmicos que podem ser reguladores da deposição nesse ambiente;

(4) Para melhor detalhamento da dinâmica de sedimentos, recomenda-se a utilização de modelos numéricos para simulação do comportamento do ambiente considerando diferentes configurações do canal e a inclusão de obras de engenharia costeira de pequeno porte, buscando, assim, reduzir as taxas de sedimentação observadas no ambiente por meio da alteração das configurações hidrodinâmicas.

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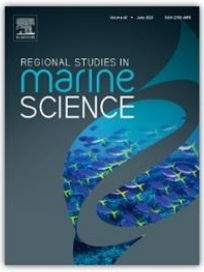
ANEXOS

ANEXO A – Comprovante de aceite do artigo 1

Sedimentation processes in the navigation channel of Patos Lagoon Estuary, southern Brazil

Article reference	RSMA_102931
Journal	Regional Studies in Marine Science
Corresponding author	Marine Silva
First author	Marine Silva
Received at Editorial Office	20 Sep 2022
Article revised	8 Mar 2023
Article accepted for publication	13 Mar 2023
DOI	10.1016/j.rsma.2023.102931



ISSN 2352-4855

Last update: 2 May 2023

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Bibliographic information

Volume/Issue
61C

ANEXO B – Comprovante de submissão do artigo 2

Continental Shelf Research

Marine Jusiane Bastos da Silva | Logout

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Submissions Being Processed for Author

Page: 1 of 1 (1 total submissions) Results per page 10

Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status
Action Links	CSR-D-23-00110	Sediment patterns in the navigation channel of the Patos Lagoon Estuary, Brazil, between 2005 and 2009	Apr 11, 2023	May 26, 2023	Under Review

Page: 1 of 1 (1 total submissions) Results per page 10

ANEXO C – Comprovante de submissão do artigo 3

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Title
SILTATION IN THE NAVIGATION CHANNEL OF PATOS LAGOON ESTUARY, BRAZIL, CONSIDERING THE CURRENT CONFIGURATION OF THE JETTIES AND THE CHANNEL

Type
Research

Journal
Geo-Marine Letters

Submission ID
dc3a3230-382c-4769-9896-079ffa827f00

ANEXO I
Título da Tese:
"PROCESSOS SEDIMENTARES NO CANAL DE ACESSO AO ESTUÁRIO DA LAGOA DOS PATOS, BRASIL"
Área de Concentração: Geologia Marinha
Autora: **Marine Jusiane Bastos da Silva**
Orientador: Prof. Dr. Iran Carlos Stalliviere Correa Coorientador: Prof. Dr. Jose Antonio Scotti Fontoura
Examinador: Prof. Dr. Jair Weschenfelder
Data: 20/06/2023
Conceito: A (Excelente)

PARECER:

A Tese de Doutorado da aluna do Programa de Pós-Graduação em Geociências (PPGGEO) da UFRGS, *Marine Jusiane Bastos da Silva,* aborda uma temática relevante em relação aos fatores morfológicos e dinâmicos que governam os processos sedimentares dos canais estuarinos em planícies costeiras.

A estruturação da Tese de Doutorado segue os requisitos e normativas de '*tese por artigo*', requeridas pelo PPGGEO/UFRGS, com três artigos submetidos à publicação em revistas científicas nos estratos Qualis-CAPES indicados, os quais são precedidos de um texto introdutório e seguidos das considerações finais e síntese da tese.

Os três artigos científicos, submetidos à publicação em importantes revistas relacionadas a essa temática, são muito bem ilustrados, com figuras e mapas que demonstram de forma detalhada a evolução da morfologia de fundo do canal/área de estudo do Porto de Rio Grande e a sua relação com os aspectos hidrodinâmicos.

A apresentação da Tese de Doutorado foi feita de forma segura pela autora, demonstrando domínio da temática e esclarecendo todas as questões e dúvidas pendentes quando arguida pelos membros da Banca Examinadora.

Desta forma, considero essa Tese de Doutorado uma contribuição científica importante, com uma abordagem inédita no estudo evolutivo, morfológico e de dinâmica sedimentar do Porto de Rio Grande/RS, com repercussões em ambientes costeiros análogos.

Assinatura: Data: 20/06/2023

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Ciente do Orientador:

Ciente do Aluno:

ANEXO I
Título da Tese:
“PROCESSOS SEDIMENTARES NO CANAL DE ACESSO AO ESTUÁRIO DA LAGOA DOS PATOS, BRASIL”
Área de Concentração: Geologia Marinha
Autora: **Marine Jusiane Bastos da Silva**
Orientador: Prof. Dr. Iran Carlos Stalliviere Correa Coorientador: Prof. Dr. Jose Antonio Scotti Fontoura
Examinador: Prof. Dr. Miguel da Guia Albuquerque
Data: 20/06/2023
Conceito: “A” (EXCELENTE)
PARECER: Inicialmente agradeço a candidata e aos orientadores pelo convite para participar da avaliação da Tese de doutorado intitulada “Processos sedimentares no canal de acesso ao estuário da Lagoa dos Patos, Brasil”. A temática escolhida pela candidata é de grande relevância, uma vez que se trata de um dos Portos mais importantes da região sul do Brasil, e de um dos sistemas estuarinos mais importantes do Atlântico Sul. Minha avaliação será dividida em dois pontos: aspectos gerais e apontamentos referente a cada capítulo/ artigo. Em termos gerais, o corpo do documento e os artigos/ capítulos estão bem desenvolvidos e encadeados. A tese apresenta uma robustez considerável de dados! Em relação as considerações no documento, o primeiro resumo apresentado no documento carece de dados para embasar sua escrita. Um exemplo disso está no trecho que diz “A *análise dos dados revelou informações inéditas sobre as características do fundo e padrões de sedimentação. Os resultados indicaram uma variação significativa nas taxas líquidas de sedimentação...*”. Esses números, pelos menos os principais, não foram inseridos no resumo. Eu até entendo que o resumo é o último item a ser desenvolvido em uma tese ou dissertação, e que qualquer candidato deixa para o final. No entanto, o mesmo merece a mesma atenção dada ao restante do trabalho. Em relação ao Capitulo 01, no tópico introdução, observar que o 2º parágrafo está deslocado do restante do texto. Na construção de um texto introdutório, nós devemos partir do global para o local. Nesse sentido, o 2º parágrafo deveria ser o 5º parágrafo da sua introdução. Demais pequenos apontamentos estão inseridos no documento “pdf” encaminhado. No tópico “hipóteses”, é levantada a hipótese que “levantamentos batimétricos são uma forma precisa de determinação das características morfológicas do canal”. No desenvolvimento da tese não consta a informação se existe (ou é recomendado) um período mínimo para realização de batimetrias, a depender da época (no caso primavera-verão e outono-inverno). Para um dos artigos submetidos seria interessante trazer essa informação/ consideração. A motivação para realização do estudo e todos os objetivos, na minha avaliação estão de acordo. A descrição da área de estudo está coerente, contudo, seria interessante padronizar as

simbologias, como feito nos artigos. Exemplo: foi usada simbologia “NE-SO”, quando na realidade deveria ser utilizado “NE-SW”. O estado da arte está muito bem construído, mas, ele poderia estar mais atualizado se a candidata mencionasse as questões do uso do sensoriamento remoto na determinação de batimetrias. Esse comentário é pontuado, uma vez que se necessita de batimetrias *in situ* para calibrar batimetrias obtidas por imagens. Na atualidade (últimos 5 anos) já existem muitos trabalhos referentes ao assunto. O tópico materiais e métodos também se encontra bem desenvolvido. Em relação ao 1º artigo (capítulo 02), eu não tenho comentários específicos tendo em vista que o mesmo já foi avaliado pelos revisores do periódico *Regional Studies in Marine Science*, sendo que já se encontra publicado. Para o segundo artigo (capítulo 03), sugiro reformular o 3º parágrafo da introdução. No trecho dos materiais e métodos, no subtópico dados batimétricos, é importante indicar qual a zona UTM da área de estudo. É interessante também justificar porque foi escolhida a krigagem como método estatístico. Nos resultados, o parágrafo 1 (pág 86 do pdf.) precisa de ajustes. Também é necessário discutir melhor o resultado dos DEMs. No terceiro artigo (capítulo 04), reformular a última frase da introdução. O subitem 4.4.2 e o 2º parágrafo da discussão também necessitam de uma reformulação. Os demais comentários estão descritos no documento pdf encaminhado pela candidata. No mais, este avaliador da PARECER FAVORÁVEL e CONCEITO “A” (EXCELENTE) para a Tese de Doutorado apresentada pela candidata Marine Jusiane Bastos da Silva.

Assinatura: Data: 20/06/2023.

Ciente do Orientador:

Ciente do Aluno:

ANEXO I

Título da Tese:

“PROCESSOS SEDIMENTARES NO CANAL DE ACESSO AO ESTUÁRIO DA LAGOA DOS PATOS, BRASIL”

Área de Concentração: Geologia Marinha

Autora: **Marine Jusiane Bastos da Silva**

Orientador: Prof. Dr. Iran Carlos Stalliviere Correa
Coorientador: Prof. Dr. Jose Antonio Scotti Fontoura

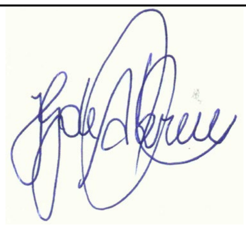
Examinador: Prof. Dr. José Gustavo Natorf de Abreu

Data: 20/06/2023

Conceito: A -Excelente

PARECER:

Parecer favorável à aprovação em caráter de excelência.
Tese muito bem elaborada em termos de estrutura, conceitos, análises e discussões. A defesa acompanha a ótima qualidade da tese apresentada impressa.

Assinatura:  Data: 21 de junho de 2023

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