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CARACTERIZAÇÃO DO RISCO COSTEIRO AOS IMPACTOS INDUZIDOS POR MARÉS DE TEMPESTADE NA COSTA CENTRAL DE SANTA CATARINA

Florianópolis
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Dissertação submetida ao Programa de Pós Graduação em Oceanografia da Universidade Federal de Santa Catarina para a obtenção do título de Mestre em Oceanografia
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Karen Cristina Pazini

Caracterização do risco costeiro aos impactos induzidos por marés de tempestade na costa central de Santa Catarina

O presente trabalho em nível de mestrado foi avaliado e aprovado por banca examinadora composta pelos seguintes membros:

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Certificamos que esta é a **versão original e final** do trabalho de conclusão que foi julgado adequado para obtenção do título de Mestre em Oceanografia.

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Prof. Dr. Jarbas Bonetti Filho
Orientador

Florianópolis, 2021.

Este trabalho é dedicado a você leitor.

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“Feliz é aquele que transfere o que sabe e aprende o que ensina”

Cora Coralina

RESUMO

Esta pesquisa objetivou a identificação de áreas críticas ao risco de inundação e erosão induzidas por marés de tempestade no setor costeiro central de Santa Catarina, uma área densamente habitada e reconhecida pela importante geração de bens e serviços ecossistêmicos às comunidades locais. Para este fim, a primeira fase da metodologia CRAF – '*Coastal Risk Assessment Framework'* (Sistema de Avaliação de Risco Costeiro) foi implementada em escala regional, considerando-se a probabilidade de ocorrência dos impactos relacionados aos perigos para os períodos de retorno de 10 e 50 anos. Baseada na utilização de modelos empíricos e análise espacial, a ferramenta une diferentes indicadores de impacto e exposição em um único índice, permitindo a comparação entre os setores e a identificação de áreas de maior risco. Os resultados obtidos demonstram que Florianópolis e Tijucas são os municípios sob maior risco de erosão e inundação no Setor Costeiro Central. Estes mesmos municípios apresentam uma combinação de características intrínsecas, relacionadas aos parâmetros hidrometeorológicos e sua herança geológica, que os tornam naturalmente mais susceptíveis à eventos extremos. Somado a estes fatores, aspectos relacionados ao padrão de ocupação dessas áreas destacam alguns dos setores historicamente mais atingidos e impactados por eventos de marés de tempestade. A análise dos resultados obtidos no período de retorno mais longo sugere, além da perda instantânea de grandes faixas de areia, a exposição futura de construções humanas e estradas locais. Apesar da necessidade de simplificação dos parâmetros utilizados pelo modelo original, a metodologia utilizada mostrou-se adequada para uma primeira etapa de avaliação de risco. Além disso, o estudo mostrou algumas alternativas que podem ser realizadas para a implementação da metodologia CRAF em áreas que não possuem uma infraestrutura de dados espaciais disponível.

Palavras-chave: Risco costeiro. Erosão. Inundação. Metodologia CRAF.

ABSTRACT

This research aimed to identify hotspots of storm-induced flood and erosion impacts in the central coastal sector of Santa Catarina state, a highly developed area recognized by its importance in the offer of goods and ecosystem services for the local communities. To this end, the first phase of the CRAF (Coastal Risk Assessment Framework) framework was implemented at a regional scale, considering the probability of hazards occurrence for the 10 and 50 years return periods. Based on the application of empirical models and spatial analysis, the tool combines different indicators of hazard and exposure into a single index, allowing the comparison between sectors and the hotspots identification. The results obtained show that Florianópolis and Tijucas are the municipalities most at risk of erosion and flood in the study area. The same municipalities have a combination of intrinsic characteristics related to hydrometeorological patterns and their geological heritage that make them naturally more susceptible to extreme events. Moreover, aspects related to the pattern of occupation in these areas increase the exposure of some sectors historically most affected and impacted by storm surge events. The results obtained for the longer time frame suggests, in addition to the instant loss of large sand strips, future exposure of human assets, including the local road network. In addition, the study showed some alternatives that can be performed for the implementation of the CRAF tool in areas without an available spatial data infrastructure.

Keywords: Coastal risk. Erosion. Flood. CRAF methodology.

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LISTA DE ABREVEATURAS E SIGLAS

BU	Atividades econômicas (*Business*)
CAPES	Coordenadoria de Apoio à Pesquisa de Ensino Superior
CI	Índice Costeiro (*Coastal Index*)
CNES	Registro Nacional de Estabelecimentos de Saúde
CRAF1	Sistema de Avaliação de Risco Costeiro fase um (*Coastal Risk Assessment Framework phase one)*
CVI	Índice de Vulnerabilidade Costeira (*Coastal Vulnerability Index*)
CNPq	Conselho Nacional de Desenvolvimento Científico e Tecnológico
DEINFRA	Departamento de Infraestrutura do estado de Santa Catarina
DHN	Diretoria de Hidrografia e Navegação
EM-DAT	Banco de dados de eventos emergenciais (*Emergency Events Database*)
FAPESC	Fundação de Amparo à Pesquisa de Santa Catarina
G.E.V.	Valor extremo generalizado (*Generalized Extreme Value*)
GIS	Sistema de Informações Geográficas (*Geographic Information System*)
GOST	Banco de dados global de ondas e marés oceânicas (*Global Ocean Surge and Tide database*)
IBGE	Instituto Brasileiro de Geografia e Estatística
Iexp	Indicador de exposição (*Exposure indicator*)
Ih	Indicador de perigo de impacto (*Hazard impact indicator*)
IH-AMEVA	Análise Matemática e Estatística de Variáveis Ambientais (*Mathematical and Statistical Analysis of Environmental Variables*)
LOC	Laboratório de Oceanografia Costeira
LU	Uso do Solo (*Land Use*)
MA	Maré Astronômica
MM	Maré Meteorológica
NM	Nível Médio do Mar
RIMPEEX-Sul	Rede Integrada para Monitoramento e Previsão de Eventos Extremos na Região Sul
ROW	Banco de dados de ondas oceânicas regionais (*Regional Ocean Waves database*)
SDS	Secretaria do Estado do Desenvolvimento Econômico Sustentável

SEAP	Secretaria Especial de Agricultura e Pesca
SED-SC	Secretaria de Educação do Estado de Santa Catarina
SV	Vulnerabilidade Social (*Social Vulnerability*)
SVI	Índice de Vulnerabilidade Social (*Social Vulnerability Index*)
T	Período de retorno
TS	Sistema de Transportes (*Transport System*)
TWL	Cota de Inundação (*Total Water Level*)
UFSC	Universidade Federal de Santa Catarina
UNISDR	Escritório das Nações Unidas para a Redução do Risco de Desastres (*United Nations Office for Disaster Risk Reduction*)
UT	Utilidades (*Utilities*)

LISTA DE SIMBOLOS

A	Parâmetro de sedimentação do grão
A_i	Área ocupada pela classe de uso do solo
A_t	Área total do setor
B	Altura da duna frontal
C	Parâmetro da forma
D_{50}	Tamanho médio do sedimento
g	Aceleração gravitacional
Hb	Altura de quebra de onda
hb	Profundidade de quebra de onda
H_s	Altura de significativa de onda em águas profundas
$Hs,_{AM}$	Valor máximo atingido no ano
k	Constante de Dean
L_0	Comprimento de onda em águas profundas
m	Declividade do perfil praial
M	Parâmetro de localização
Pr	Parâmetro de distribuição de Gumbel
R_∞	Retração potencial máxima
R_t	Retração potencial
Ru	*Wave Runup*
$R_{2\%}$	*Wave Runup* atingido por 2% dos casos
S	Variação do nível do mar
Tanα	Declividade da face da praia
TD	Tempo de duração da tempestade
T_S	Tempo de resposta do perfil praial a um dado evento
V	Valor atribuído à classe de uso de solo
X_b	Distância da costa à profundidade de quebra de onda
β	Taxa de retração adimensional da tempestade
ξ	Parâmetro de similaridade de surf

SUMÁRIO

1 INTRODUÇÃO

A zona costeira situa-se na interface entre o continente, o oceano e a atmosfera. Trata-se de um ambiente de extrema complexidade, onde a atuação de processos variados, decorrentes da interação destes sistemas, caracterizam as partes mais dinâmicas da superfície da Terra (WOODROFFE, 2002). Estas áreas, de relevante importância econômica e ambiental, são historicamente atingidas por eventos de baixa frequência e alto impacto, que colocam em risco estruturas, populações, e a integridade de diferentes ecossistemas.

Estudos apontam que o aumento da frequência de eventos extremos relacionados às mudanças climáticas podem intensificar os impactos relacionados às zonas costeiras (VITOUSEK et al., 2017; VOUSDOUKAS et al., 2018). Além disso, o incremento de atividades antrópicas nestes ambientes contribui diretamente para o aumento da exposição a perigos costeiros (IPCC, 2014).

Dentre os eventos extremos relacionados às zonas costeiras, destacam-se as marés de tempestade, que podem ser definidas como sobre-elevações do nível do mar geradas por forçantes atmosféricas (FLATHER, 2001). Grandes perdas a âmbito mundial vinculam-se a eventos como este (VON STORCH, 2014a).

A região sul do Brasil é historicamente afetada por eventos de marés de tempestade associados à passagem de frentes frias e ciclones extratropicais (PARISE et al., 2009; MACHADO et al., 2010). Em Santa Catarina, cujo litoral é marcado por condições oceanográficas e meteorológicas de forte dinâmica, episódios de inundação e erosão costeira induzidos por marés de tempestade são recorrentes, e têm causado sérios prejuízos e transtornos à comunidade local (RUDORFF et al., 2014). Especificamente no Setor Costeiro Central, já foram descritos processos erosivos em diversas praias e sérios danos materiais associados a estes eventos e à crescente ocupação da orla nas últimas décadas (SIMÓ & HORN FILHO, 2004; HORN FILHO, 2006; RUDORFF et al., 2014; KLEIN et al., 2016a) .

Como resposta às repercussões associadas, as diferentes componentes do risco (perigo, exposição e vulnerabilidade) foram analisadas com diferentes métodos (e as vezes usando diferentes terminologias) ao longo do litoral Catarinense em escala estadual (BAIXO, 2015; SERAFIM & BONETTI, 2017; BONETTI et al., 2018; SERAFIM et al., 2019). Além disso, diversos estudos que abrangem o setor costeiro central foram também realizados em escala de maior detalhe (MAZZER et al., 2008; RUDORFF & BONETTI, 2010; MUSSI, 2011; MULER & BONETTI, 2014; KLEIN et al., 2016b; MUSSI et al., 2018; SANTOS & BONETTI, 2018; SILVEIRA & BONETTI, 2019; LIMA & BONETTI, 2020).

Apesar dessa diversidade de investigações, ainda não foi apresentada uma análise integrada de risco em termos probabilísticos para a área em questão. Neste contexto, o presente estudo propõe uma análise de risco à erosão e inundação induzidas por eventos de marés de tempestade no setor costeiro central de Santa Catarina por meio da aplicação da metodologia CRAF1 '*Coastal Risk Assessment Framework – phase one*' (Sistema de Avaliação de Risco Costeiro – Fase um).

Desenvolvida a âmbito do projeto RISC-KIT (VAN DONGEREN et al., 2018), trata-se de uma ferramenta, baseada no Índice de Vulnerabilidade Costeira (CVI) para a identificação de setores de maior risco. Seus principais diferenciais incluem a avaliação de perigos através de modelos empíricos, a consideração da probabilidade de ocorrência dos perigos que afetam os receptores, e a avaliação dos impactos relacionados a diferentes grupos de receptores (VIAVATTENE et al., 2017), possibilitando uma representação mais integrada das complexas variáveis que atuam na zona costeira.

A metodologia CRAF1 foi originalmente desenvolvida e validada para o continente Europeu, e apesar de aplicada em diferentes contextos morfológicos, oceanográficos e sociais (ex. ARMAROLI & DUO, 2018; AUCELLI et al., 2018; CHRISTIE et al., 2018; DE ANGELI et al., 2018; JIMENEZ et al., 2018; PLOMARITIS et al., 2018), é a primeira vez que a metodologia é implementada em uma condição de escassez de dados com alta resolução espacial. Dessa forma, o presente trabalho também busca propor algumas alternativas para o tratamento de variáveis previstas pelo modelo em áreas que não dispõem de uma infraestrutura de dados espaciais adequada.

1.1 QUADRO CONCEITUAL

A análise de risco de sistemas antrópicos e naturais a perigos adversos converge estudos de diferentes campos de pesquisa dentro de uma mesma temática. Cada qual utiliza seu tipo de abordagem e definição para termos que frequentemente se referem a processos similares, dificultando aproximações integradas do ponto de vista conceitual. Em decorrência, tem-se uma crescente produção literária com termos correlacionados de forma incerta, dentre eles risco, vulnerabilidade e perigo (BROOKS, 2003).

Muitas instituições internacionais com pesquisas voltadas para a prevenção e redução de desastres naturais frente à mudanças climáticas adotaram definições próprias para termo risco, que é frequentemente utilizado para se referir à combinação da probabilidade de um perigo e suas consequências (UNISDR, 2009; IPCC, 2014; VAN DONGEREN et al., 2014;

RANGEL-BUITRAGO et al., 2020). Neste contexto, risco pode ser visto como um elemento externo ao sistema, sendo o produto de um evento de perigo e a vulnerabilidade dos elementos expostos (BIRKMANN, 2007).

Da mesma forma para a EM-DAT (CRED, 2018) organização belga que se propõe a gerar dados estatísticos de desastres em perspectiva global, risco trata-se de perdas esperadas (de vidas, pessoas feridas, bens danificados e atividade econômica interrompida) devido a um perigo particular para uma determinada área e período de referência. Para a Secretaria de Defesa Civil (BRASIL, 2017), o termo designa o potencial de ocorrência de ameaça de desastre em um cenário socioeconômico e ambiental vulnerável.

Nota-se que o termo risco é frequentemente relacionado ao potencial, quando o resultado é incerto, por consequências adversas. Desse modo, o processo de análise de risco remete a utilização de uma metodologia para determinar a natureza e extensão do mesmo, analisando os perigos potenciais e avaliando as condições existentes de vulnerabilidade que, juntos, poderiam prejudicar os elementos expostos (UNISDR, 2009).

O termo vulnerabilidade por sua vez tem sido conceituado de maneira desconforme por acadêmicos de diferentes linhas de pesquisa, havendo por vezes, grande inconsistência em terminologias adotadas. Contudo, constata-se que a vulnerabilidade é específica para um determinado local ou grupo ou setor, não havendo portanto, uma definição única que se encaixe em todos os contextos de avaliação (HINKEL & KLEIN, 2006; NGUYEN et al., 2016).

Para o Painel Intergovernamental de Mudanças Climáticas (2014) vulnerabilidade pode ser entendida como a propensão ou predisposição de um sistema a ser afetado adversamente. A UNISDR (2009) define o termo como sendo o conjunto de características e circunstâncias de uma comunidade, sistema ou ativo que o tornam suscetível aos efeitos prejudiciais de um perigo. Definições mais amplas no entanto são comumente utilizadas, onde incluem também a exposição do elemento, relacionando-o a um perigo específico ou a uma gama de perigos (BROOKS, 2003; FUSSEL, 2005; HINKEL & KLEIN, 2006; NGUYEN et al., 2016).

Perigo pode ser considerado como um processo ou fenômeno que pode causar perda de vida, ferimentos, impactos, danos à propriedade, perda de meios de subsistência e serviços, rupturas sociais e econômicas, ou danos ambientais (UNISDR, 2009; RANGEL-BUITRAGO et al., 2020). Perigo costeiro pode ser definido, de forma mais específica, como um fenômeno natural que expõe a zona litorânea ao risco de dano ou outro impacto e efeitos adversos

(GORNITZ, 1991). Os perigos costeiros de origem natural relacionam-se a uma variedade de fatores geológicos, meteorológicos, hidrológicos, oceanográficos e biológicos, podendo às vezes atuar em combinação.

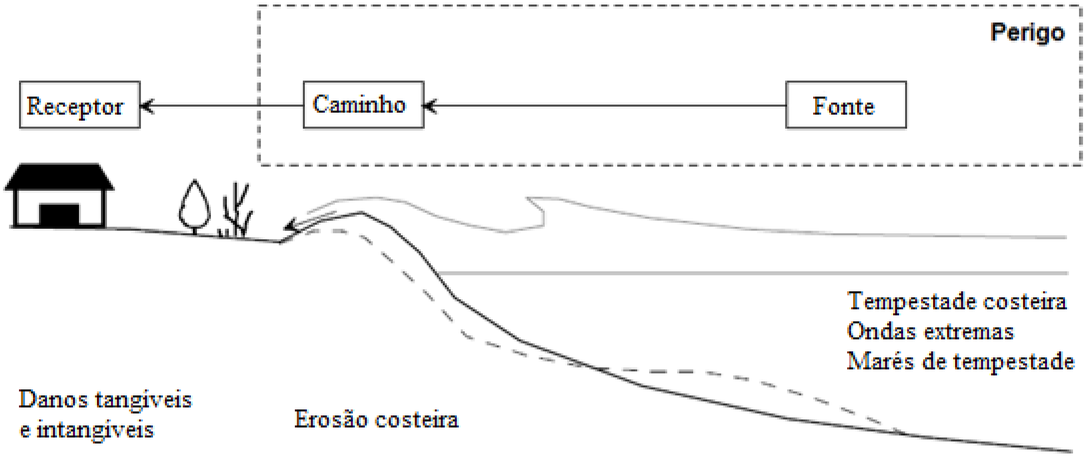
Diante da existência de uma ampla gama de definições, a busca por um quadro conceitual bem definido permite análises comparativas e de evolução, favorecendo ações de planejamento. Dessa forma, afim de delimitar um campo mínimo de conhecimento, são definidos a seguir os termos a serem utilizados (Quadro 1), conforme Van Dongeren et al. (2014).

Quadro 1. Definição dos termos a serem utilizados

Terminologia	**Definição**
Risco	Produto da probabilidade de ocorrência do perigo e suas consequências
Perigo	Fenômeno ou evento físico com potencial para resultar em danos ou prejuízo
Vulnerabilidade	Propensão de um receptor a sofrer danos.
Sensibilidade/Susceptibilidade	Nível potencial natural de perdas associadas às características do Perigo
Receptor	Entidades ameaçadas diretamente (expostas ao perigo) ou indiretamente
Indicador	Estimação qualitativa ou quantitativa do estado de risco, vulnerabilidade ou susceptibilidade

Neste trabalho, risco é definido como o produto da probabilidade de um perigo e suas consequências (UNISDR, 2009). Estas consequências ou impactos são compostas por dois fatores: a exposição direta e a vulnerabilidade (propensão de um receptor a sofrer danos). A definição tem sua origem no modelo '*Source-Pathway-Receptor*' (Fonte-Caminho-Receptor) (SAMUELS et al., 2005), um modelo simples e conceitual para representar sistemas e processos que levam a uma consequência particular. Nesta abordagem, para que um risco ocorra, deve haver um perigo que consista em uma 'fonte' ou evento iniciador; um 'receptor' e uma via entre a fonte e o receptor (Figura 1.1).

Figura 1.1 Modelo '*Source-Pathway-Receptor*' (Fonte-Caminho-Receptor)



Fonte: Modificado de Jiménez et al. (2008)

1.2 ANÁLISE DE RISCO E VULNERABILIDADE

A zona costeira é um ambiente altamente complexo e vulnerável. Dessa forma, a avalição dos riscos nestes locais possui caráter estratégico à medida que auxilia no processo de gerenciamento e tomada de decisões em relação à redução de impactos e aumento de resiliência de comunidades costeiras.

Muitas metodologias foram desenvolvidas para avaliar o risco e vulnerabilidade das áreas costeiras a diferentes perigos. Neste contexto, a diversidade e imprecisão de conceituações contribuíram para o aparecimento de uma grande variedade de abordagens (BROOKS, 2003).

Destaca-se neste meio, o surgimento de um grande número de metodologias baseadas em análise espacial, não apenas pela boa representação dessas componentes em Sistemas de Informação Geográfica, como também devido ao aumento de recursos analíticos provenientes desta área (BONETTI & WOODROFFE, 2016).

Um dos modelos largamente utilizado e adaptado para diversas áreas é o denominado Índice de Vulnerabilidade Costeira (CVI). Desenvolvido por Gornitz et al. (1991), inicialmente esta abordagem considerou oito indicadores para avaliar a vulnerabilidade de uma área costeira à subida relativa do nível do mar. Esses indicadores representavam o setor costeiro essencialmente em termos físicos. A metodologia foi largamente adotada, provavelmente devido à facilidade de aplicação e possibilidade de combinar diferentes tipos de variáveis em um único índice (COOPER & MCLAUGHLIN, 1998). Posteriormente, muitas modificações foram feitas, no entanto, a abordagem continuou com limitações relacionadas à não consideração de dados socioeconômicos.

Embora muitos estudos de vulnerabilidade social tenham sido desenvolvidos (CUTTER et al., 2003; RYGEL et al., 2006; BORUFF & CUTTER, 2007; HUMMELL & CUTTER 2016), nota-se a carência de avaliações locais em contextos espacialmente definidos de perigos (MAVHURA et al., 2017).

Algumas abordagens híbridas passaram a ser adotadas para sanar tais limitações (MCLAUGHLIN et al., 2002; BORUFF et al., 2005; BIRKMANN et al., 2013) no entanto os índices combinados passaram a ser mais complexos. Apesar do valor econômico de alguns deles, que são fáceis de calcular, em geral, as variáveis investigadas são difíceis de avaliar devido à sua grande distribuição espacial e temporal ou às suas características intrínsecas (RANGEL-BUITRAGO & ANFUSO, 2015)

Segundo NGUYEN *et al.* (2016), até agora, parece não ter havido uma estrutura ou metodologia convincente para quantificar e comparar a vulnerabilidade às mudanças climáticas em escalas dependentes do espaço, com relação às componentes de exposição, sensibilidade (ou susceptibilidade) e capacidade adaptativa. Os autores enfatizam ainda que mesmo se tratando da mesma abordagem, a variabilidade de classificação e categorização dos graus de vulnerabilidade dificultam a comparação de resultados obtidos para diferentes áreas.

Paralelamente a este contexto, foi desenvolvido a âmbito da União Europeia, o projeto RISC-KIT, que proporciona uma ampla gama de ferramentas abertas para a análise de risco em escala regional visando a redução de impactos e desastres costeiros (VAN DONGEREN *et al.*, 2018). O projeto propõe a utilização de um esquema analítico destinado à identificação de áreas críticas ao risco em escala regional, baseada na abordagem CVI.

A metodologia foi testada com êxito em dez estudos de caso que se distribuem ao longo das costas regionais europeias, e abrangem características diversas, em termos de configuração geomorfológica, uso da terra, tipo de perigo, condições hidrometeorológicas, aspectos socioeconômicos, culturais e ambientais (FERREIRA *et al.*, 2017). A estrutura mostra-se, desse modo, flexível quanto à adaptação a diferentes necessidades, facilitando ao mesmo tempo a comparabilidade entre áreas de estudo distintas, ao passo que padroniza as diferentes classificações através da abordagem CVI. Conceitos mais abrangentes do ponto de vista sistêmico são também abordados, incluindo a possibilidade de análise multirrisco, a consideração da probabilidade dos perigos que afetam os receptores, e a avaliação de impactos indiretos (VIAVATTENE et al., 2017).

Diante do quadro apresentado, nota-se que há uma necessidade constante de aprimoramento das diferentes metodologias em vista da necessidade de melhor representar as complexas variáveis que permeiam o ambiente costeiro, sem contudo perder e simplificar demasiadamente sua representação. Ao mesmo tempo faz-se necessário o desenvolvimento de metodologias práticas, que sejam de fácil acesso ao gestor e que permitam a comparabilidade entre diferentes áreas.

1.3 INUNDAÇÃO COSTEIRA

Inundação é um termo que pode ser definido como a submersão temporária de um lugar que normalmente não é coberto por água (FEMA, 2008). Inundações costeiras são geralmente causadas pela combinação de altos níveis de água e ação de ondas. Consequentemente, para uma estimativa adequada da cota de inundação (TWL), faz-se necessário a análise de probabilidade conjunta de todos os parâmetros não estacionários que influenciam no nível total de água, somados ao nível médio do mar (VIAVATTENE et al., 2015a).

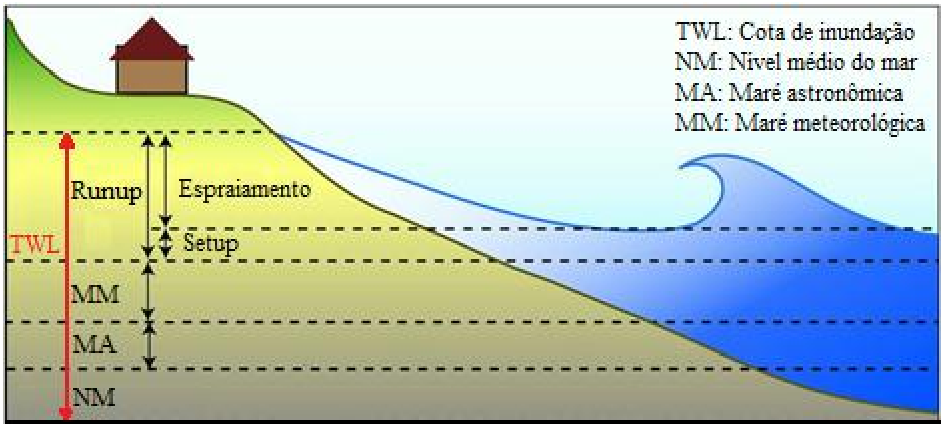
Portanto, a variável que representa a cota de inundação é composta por diferentes contribuições, e pode ser descrita através da seguinte relação (Equação 1.1):

$$\mathrm{TWL} = \mathrm{NM} + \mathrm{MA} + \mathrm{MM} + Ru \qquad (1.1)$$

Onde NM é a componente que define o nível médio do mar; MA, a maré astronômica; MM, a maré meteorológica e *Ru*, o *Run-up* calculado. Este último caracteriza o aumento do nível induzido pelo empilhamento de água na costa (SHORT, 1999). *O run-up* é composto pela sobrelevação do nível médio do mar causada pela quebra de ondas (*wave setup*) e pelas oscilações em torno da zona de espraiamento (*wave swash*) (HOLMAN & SALENGER, 1985).

A Figura 1.2 ilustra de forma simplificada as componentes que definem a cota de inundação em um determinado ponto da costa.

Figura 1.2 Diagrama esquemático das componentes que definem a cota de inundação (TWL)



Fonte: Modificado de Vitousek et al. (2017)

1.3.1 Cálculo do Runup

O *runup* é um fenômeno complexo, que depende do nível de água local, condições da onda incidente (altura, período, inclinação, direção) e a natureza da praia ou estrutura *runup* (inclinação, refletividade, altura, permeabilidade, rugosidade) (VIAVATTENE et al., 2015a).

O cálculo deste parâmetro é necessário para a definição da elevação máxima potencial do nível de água na linha de costa durante um determinado evento, e sua avaliação é geralmente feita através da aplicação de modelos empíricos, que preveem sua magnitude como uma função das condições de onda e declividade da face da praia.

Um dos modelos mais utilizados foi proposto por Holman (1986). Os autores fizeram testes para cálculo de *runup* em praias arenosas reais, com declividades variadas. A relação encontrada entre o *runup* atingido por 2% das ondas ($R_{2\%}$) foi (Equação 1.2):

$$R_{2\%} = Hs\,(0.83\xi + 0.2) \qquad (1.2)$$

A equação requer parâmetros como altura de significativa das ondas em águas profundas (H_s) e o parâmetro de similaridade de surf (ξ), que por sua vez, relacionam-se de acordo com seguinte equação (1.3):

$$\xi = \tan\alpha / \sqrt{H_s/L_0} \qquad (1.3)$$

Onde *tanα* é o declive da face da praia e L_0 é o comprimento de onda em águas profundas.

1.4 EROSÃO COSTEIRA

Um dos mais relevantes impactos induzidos por tempestades em costas sedimentares é a erosão (JIMÉNEZ et al., 2015). Este é também o primeiro processo a aparecer durante as fases iniciais da tempestade e, uma vez que a praia é modificada, relaciona-se de modo interativo com o perigo de inundação (POLLARD et al., 2018)

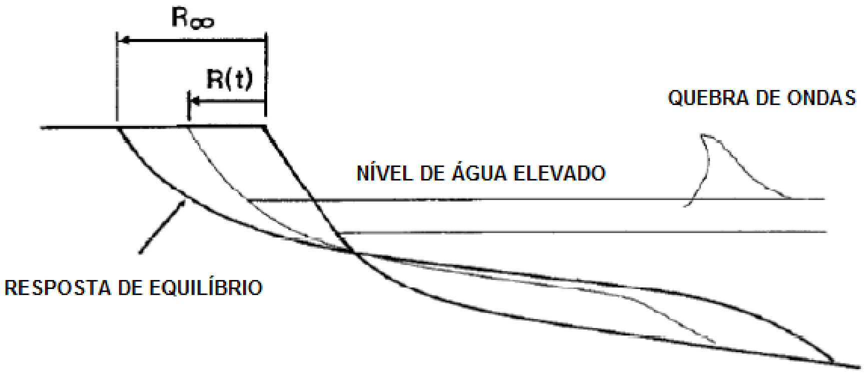
Ambos podem ocorrer de modo simultâneo ou não, levando-se em consideração que futuros impactos de inundação dependem da posição futura da linha de costa. Diante disto torna-se importante a associação destes elementos na avaliação de impactos induzidos por tempestades para identificar corretamente trechos sensíveis ao longo da costa ao impacto de eventos extremos.

O modo ideal de calcular a erosão induzida por tempestades em praias arenosas é normalmente a utilização de modelagem de processos físicos de forma detalhada, através de ferramentas desenvolvidas para simular tais condições. No entanto torna-se inviável a realização desse procedimento para a avaliação de risco em grandes escalas. Neste sentido, abordagens simples e diferentes modelos empíricos podem ser aplicados com a finalidade de proporcionar a redução de casos selecionados para análise.

Um dos modelos mais utilizados para calcular a magnitude da erosão induzida por tempestades é o método de convolução de Kriebel & Dean (1993). Nesta abordagem, a erosão é forçada pela quebra de onda e variação do nível de água devido ao evento de tempestade. O modelo assume que a alteração da face da praia não é apenas função das características do evento de tempestade, mas também função da morfologia praial.

Tendo como ponto de partida as relações propostas por Bruun (1954), a base para o método de convolução é a observação de que a resposta da praia às condições hidrometeorológicas é aproximadamente exponencial no tempo (Figura 1.3). Onde R_∞ é o recuo máximo que ocorre após o sistema atingir o equilíbrio e R(t) é a retração final da linha de costa.

Figura 1.3 Esboço de definição para a resposta do perfil da praia.



Fonte: Modificado de Kriebel e Dean (1993)

1.5 ANÁLISE DE REGIME EXTREMO

Para analisar o impacto morfodinâmico resultante de marés de tempestade, faz-se necessário estimar a probabilidade de ocorrência deste fenômeno. Isto é feito através da utilização da análise de longo prazo de regime extremo, que tem o propósito de organizar os dados e extrapolar a série temporal a valores extremos que ocorrem com baixas probabilidades de serem excedidos (MMA, 2018).

Este tipo de abordagem fornece normalmente uma sequência de valores de altura de significativa, período e direção média de onda, relacionados com sua distribuição de longo prazo e seu período de retorno (HOLTHUIJSEN, 2007).

O método mais simples para a seleção dos valores extremos é o Método de Máximos Anuais (Annual-maximum-aproach), onde o valor máximo anual é selecionado, obtendo-se N valores para N anos analisados (HOLTHUIJSEN, 2007).

Após a seleção, os valores de extremos (ou máximos anuais) podem ser calculados de acordo com a distribuição de Gumbel, que permitirá a obtenção de valores estimados dos parâmetros de distribuição teórica, a partir dos valores da amostra.

A distribuição de Gumbel de máximos é calculada através da seguinte equação (1.4):

$$Pr = \exp\left[-\exp\left(-\frac{H_{s,AM}-M}{C}\right)\right] \quad (1.4)$$

Onde, $H_{s,AM}$ é o valor máximo atingido no ano, M é o parâmetro de localização (posição da distribuição no eixo H_s) e C, o parâmetro de forma.

Finalmente, a estimativa do Período de Retorno (T), em anos, é obtida através da seguinte relação (Equação 1.5):

$$T = \frac{1}{Pr} \quad (1.5)$$

2 OBJETIVOS

2.1 OBJETIVO GERAL

Este trabalho tem como objetivo identificar áreas críticas associadas ao risco de ocorrência de processos de inundação e erosão induzidos por eventos extremos de marés de tempestade no setor costeiro central de Santa Catarina e avaliar a aplicabilidade da metodologia CRAF1 em um contexto de escassez de dados espaciais estruturados.

2.2 OBJETIVOS ESPECÍFICOS

- Avaliar, através de modelos empíricos, a magnitude dos riscos de erosão e inundação costeira induzidos por eventos extremos de marés de tempestade na área de estudo;
- Avaliar a exposição de diferentes receptores aos efeitos decorrentes da ação de marés de tempestade;
- Identificar áreas críticas ao risco de inundação e erosão e analisar os impactos potenciais para os períodos de retorno de 10 e 50 anos;
- Avaliar o desempenho da metodologia utilizada através da comparação dos resultados obtidos com dados disponíveis na literatura.

SPOTTING AREAS CRITICAL TO STORM WAVES AND SURGE IMPACTS ON COASTS WITH DATA SCARCITY: A CASE STUDY IN SANTA CATARINA, BRAZIL

Esta seção é destinada a apresentação do artigo científico a ser submetido na revista Natural Hazards, como parte dos requisitos para a obtenção do grau de mestre em Oceanografia pela Universidade Federal de Santa Catarina.

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ABSTRACT

The impacts of severe storms on the coastal zone, combined with rapid population growth in this area, has made coastal risk management an urgent need. However, integrated risk assessment can be a challenging task for many locations worldwide, as it normally requires the use of a large amount of data. The Coastal Risk Assessment Framework phase one (CRAF1), is a recently proposed analytical scheme based on empirical models and spatial analysis that combines different indicators to identify storm-induced hotspots. The methodology, however, requires accurate data at the regional scale and was conceived and validated for the European region. In this study, we show that this approach can be applied, with some simplifications, on data-poor areas, allowing the identification of hotspots considering one or multiple hazards. Here, the coastal risk was assessed for erosion and coastal flooding events with return periods of 10 and 50 years on the Santa Catarina Central Coast. The study area is characterized by the occurrence of storm-induced impacts that historically cause disruption and damage to local communities. Although the components of risk have been assessed using various methods along this sector, to date, no integrated risk analysis has been presented in probabilistic terms. Predicted scenarios for the Santa Catarina Central Coast suggest that extreme episodes may cause several impacts, exposing urban settlements as well local road systems, especially in the municipalities of Tijucas and Florianópolis. The results show that the CRAF1 is an appropriate approach for a first-level risk analysis, even when implemented with poor data resolution, as it effectively points to some of the most vulnerable stretches detected in the study area.

KEYWORDS

CRAF, flooding, erosion, extreme events, coastal risk

3 INTRODUCTION

Storm-induced waves and surges can be considered among the most important drivers of coastal flooding and erosion, often interrelated impacts that affect most locations worldwide (Kron, 2013; Von Storch, 2014). During extreme conditions, these hydro-meteorological events can produce significant changes in the coastal zone in a very short period (Morton et al., 1995), leading to economic losses and, eventually, risk to human life.

Furthermore, future projections show that storm-induced impacts will substantially increase over the years on some coasts of the world, due to climate changes and rising sea levels (Vousdoukas et al., 2018; Kirezci et al., 2020).

In this scenario, an assessment of current and future risk is required to support coastal management and policy implementation. Risk assessment is particularly important for developing countries, in which reduced resilience means the population is exposed to more severe consequences of flood and erosion than those living in developed regions (Church et al., 2008; Hanson et al., 2011; Neumann et al., 2015; UNISDR, 2018). Estimating risk in these areas can be challenging though, as data are often unavailable or present poor resolution.

The southern region of Brazil is historically affected by storm-induced waves and surges, often associated with the passage of cold fronts and extra tropical cyclones (Parise et al., 2009). On the coast of Santa Catarina state, episodes of flooding and erosion linked to these events are recurrent and have caused serious damage to the local community (Rudorff et al., 2014).

Considering the high level of exposure of the population and urban assets along the Santa Catarina Central Coast, as demonstrated by several previous studies in the area on the local scale (Mazzer et al., 2008; Rudorff and Bonetti, 2010; Muler and Bonetti, 2014; Klein et al., 2016a; Mussi et al., 2018; Santos and Bonetti, 2018; Silveira and Bonetti, 2019; Lima and Bonetti, 2020) and regional scales (CEPAL, 2012; Serafim and Bonetti, 2017; Bonetti et al., 2018; Serafim et al., 2019), this research aimed to assess the most critical sectors, considering the different levels of risk to which the coastline is submitted.

This is a novel approach, since most of the existing research is focused on vulnerability and does not take into account the probability of the impact of coastal hazards in different time-frames. The study also prioritizes the identification of hotspots in the management unit proposed in the Brazilian Coastal Management Program sectorization, which facilitates the applicability of results by decision-makers.

Moreover, the applied methodology (the Coastal Risk Assessment Framework phase one; CRAF1) was originally designed for the European context, and despite its implementation in different coastal settings (cf. Armaroli and Duo, 2018; Aucelli et al., 2018; Christie et al., 2018; De Angeli et al., 2018; Jiménez et al., 2018; Plomaritis et al., 2018), this framework has never been tested in a condition of data scarcity. In this paper, the CRAF framework was applied in an area with incipient spatial data infrastructure and low-resolution spatial information, which is also the case in several nations around the world. For this, our paper proposes an adaptation in the use of the originally recommended risk descriptors as the main strategy to overcome the aforementioned data limitation.

Here, the tool was applied with simplifications to the area of interest, and the critical sectors were identified through a combination of empirical methods and spatial analysis, highlighting, in a comparative way, priority areas for management actions and providing a valuable information basis for further detailing.

Considering that vulnerability-related terminology varies widely among researchers, which reflects the lack of consensual definitions for such terms (Bonetti and Woodroffe, 2017), it is worth clarifying that, in this study, risk is defined as the product of the probability occurrence of a hazard and its consequences (UNISDR, 2009). Susceptibility expresses the natural potential level of losses associated with the characteristics of the hazard, and vulnerability is defined as the propensity of a receptor (human assets; ecosystems) to suffer damage (Viavattene et al., 2015). In addition, the term exposure is applied to express the direct and indirect losses that receptors may have in contact with the hazard.

This article is structured as follows: section 3.1 describes the study area and the available data; section 4 presents the first phase of the CRAF1 framework and the simplifications adopted to allow the implementation of the method to the study site; section 5 shows the results; section 6 discusses the hotspots identified and finally, section 7 summarizes the main conclusions of the work.

3.1 SANTA CATARINA CENTRAL COAST AND AVAILABLE DATA

The area of interest of this work is located in South Brazil and comprises the beaches of the Santa Catarina Central Coast (SC-CC), according to the sectorization proposed by the

Brazilian Coastal Management Program (Santa Catarina, 2006) (Fig. 3.1). Waves and storm surges affect the beaches located inside the sheltered coastline between Santa Catarina Island and the mainland differently (Mussi et al., 2018; Silveira and Bonetti, 2019), and hence this sector of the coast was not considered in the analysis. The southern sector of Tijucas municipality coastline has not been analysed either, since it is a tide-dominated beach with an upper shoreface basically composed of mud flats, which induce a particular hydrodynamical behaviour to this sector (Klein et al., 2016b).

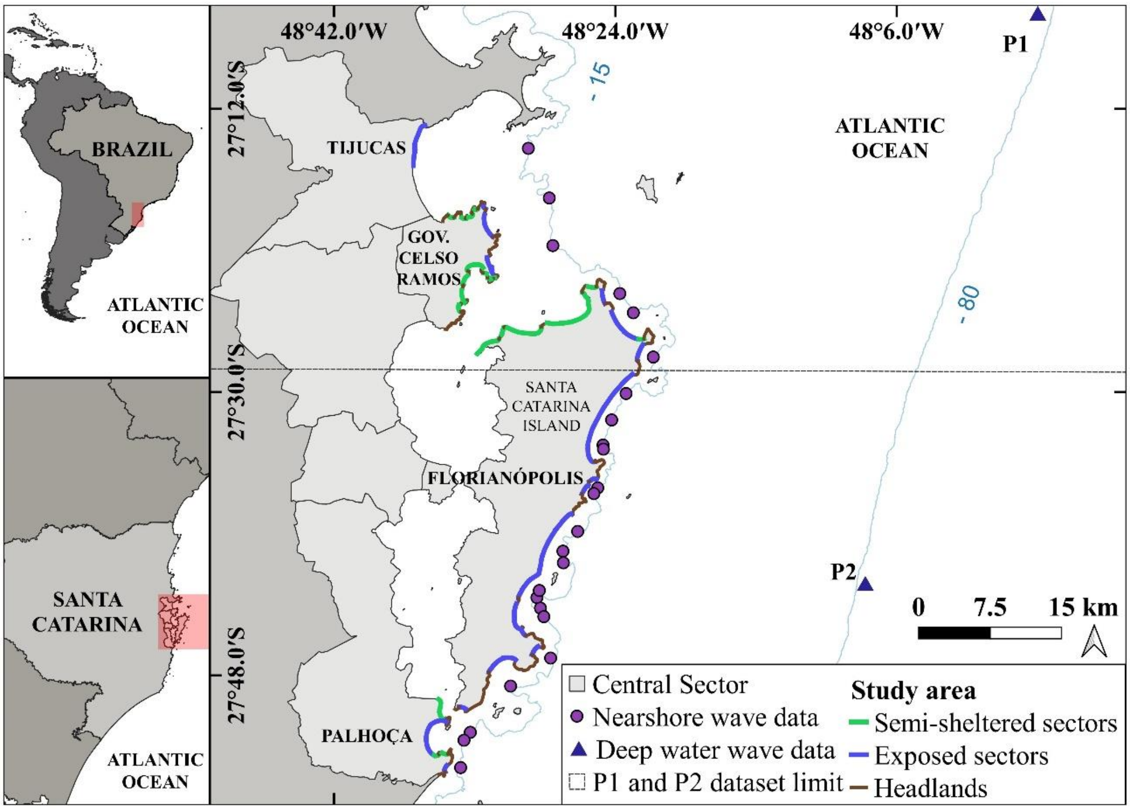

Fig. 3.1 Location of the Santa Catarina Central Coast with sectors classified according to their degree of exposure to the main wave direction. The points used for wave data extraction are also represented.

The area covers more than 100 km of coastline and includes the state capital, Florianópolis, and the municipalities of Palhoça, Governador Celso Ramos and Tijucas (Fig. 3.1). This is the most densely populated coastal region of the Santa Catarina state and is where important economic activities related to tourism, fishing, aquaculture and diverse industries stand out (Santa Catarina, 2010).

The Santa Catarina coast is exposed to waves from four main directions: low-energy conditions usually coming from the northeast quadrant, and high-energy waves arriving from east, south and southeast, with significant heights up to 6 m and a recorded maximum of 13 m individual height (Araújo et al., 2003; Melo Filho et al., 2006).

This coastal zone has a microtidal regime, with spring tides ranging from 1.05 m in the north to 0.46 in the south (Klein et al., 2016b), whereas the meteorological component of the water level (storm surge) can be as high as 1m (Truccolo et al., 2006).

The central coast of Santa Catarina state presents a high economic value, offering important goods and services (Scherer and Asmus, 2016). Nonetheless, this area is particularly prone to storm induced impacts, which cause serious property damage and demand a large amount of financial investment by the government, as highlighted by several studies (Simó and Horn Filho, 2004; Horn Filho, 2006; Rudorff et al., 2014; Klein et al., 2016b).

3.1.1 Data

The topography and bathymetry were characterized using the Digital Terrain Model available from the state's 'Secretaria de Estado do Desenvolvimento Econômico Sustentável (SDS)', with a 1 m horizontal resolution and 2.5 m altimetric accuracy (Souza et al., 2017) and from nautical charts produced by the Brazilian Navy's 'Diretoria de Hodrografia e Navegação' (DHN). Possible discrepancies regarding the different datums used for topography and bathymetry charting were minimized as proposed by Klein et al. (2016a). Beach morphology and sediment grain sizes along the coast were acquired in the field in the scope of the project RIMPEEX-Sul '(Rede Integrada de Monitoramento e Previsão de Eventos Extremos na Região Sul'; Bonetti et al., 2018).

Wave and water level data were obtained from the Regional Ocean Waves (ROW) and Global Ocean Surge and Tide (GOST) databases, a reanalysis dataset specifically validated for Santa Catarina coast (Rodríguez and Lasa, 2016) that include a 31-year period (1979–2010) with hourly temporal resolution.

Regarding the analysis of coastal exposure, the land-use data for the study area was provided by Mussi (2017); the socio-economic information was obtained from the IBGE (2011) census (see details in Supplementary Material, Annex A); the transport system was characterized with information supplied by DEINFRA (2018) and OpenStreetMap platform (OSMF, 2018);

the business information was obtained from SEAP (2008) and finally, the utility information was extracted from CNES (2018) and SED-SC (2018).

4 METHODOLOGICAL FRAMEWORK

The tool CRAF1 was applied to identify critical points in terms of coastal flooding and erosion risk. The flowchart in Fig. 4.2 summarizes the adopted methodological approach.

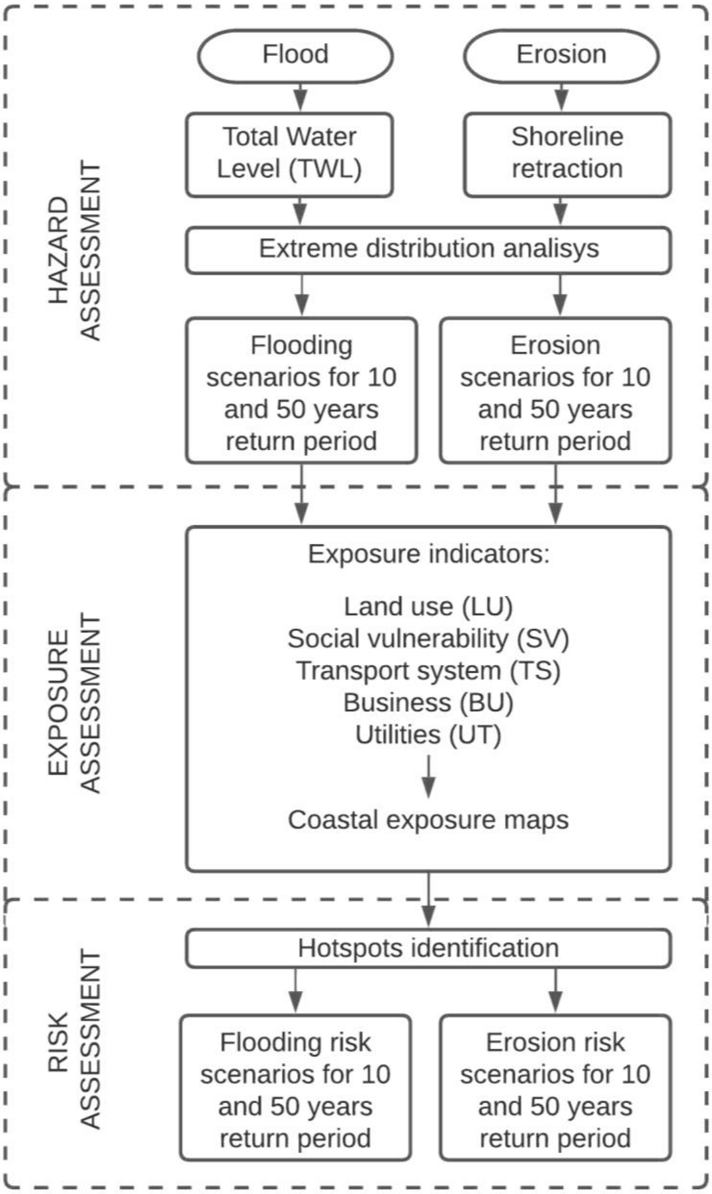

Fig. 4.2 Methodological flowchart of the risk assessment performed in this research.

The methodology consists of a screening process that allows the identification of hotspots on a large spatial scale by assessing the potential impacts for every coastal sector of approximately 1 km along the shore length. The approach combines different hazard effects

(i_h) and exposure (I_{exp}) indicators into a single value, the Coastal Index (CI), which is estimated for each sector (equation 4.1) (Viavattene et al., 2018):

$$CI = \sqrt{i_h * i_{exp}}. \qquad (4.1)$$

Here, two types of hazard effects are considered: flood and erosion. It was not possible to apply the recommended level of analytic detail, especially in the hazard assessment model, due to the non-existence of a DTM and a bathymetric chart with a fine grid and high resolution to obtain the morphological parameters at the land-ocean interface. Moreover, despite having a long time series of wave and water level data, several hydrodynamic parameters required for the application of the chosen empirical models had to be simplified, as the lack of regular bathymetry data makes it difficult to take into account the wave transformation and attenuation process in shallow waters. A comparative review showing the main challenges faced when applying the tool in the study area in its simplified form is presented in the supplementary material, Annex B.

The magnitude and extent of the different hazard effects and exposure indicators were computed separately following some assumptions and found alternatives, as described in the next sections.

4.1 COASTAL HAZARD ASSESSMENT

To estimate i_h, the magnitude of the hazard effect must be computed for a certain return period by using empirical models and converted to a hazard scale from 0 to 5 (none, very low, low, medium, high, and very high). To this end, the study area was divided into 83 representative sectors, each one covering up to a 2.5-km length of sandy beaches.

As the impact driver is strongly dependent on storm wave direction and shoreline orientation (Masselink et al., 2016), the sectors were classified according to the degree of exposure to the main wave directions that reach Santa Catarina Island: South, Southeast and East. When possible, the classification presented here was based on previous studies (Muler & Bonetti, 2014; Klein et al., 2016a; Klein et al. 2016b). Otherwise, the simple relation between the shoreline orientation and the main wave direction was taken into account for the categorization. Hereafter, 'exposed sectors' refer to the sectors exposed to waves, where there is a high angle of incidence between the main wave direction and the coastline, and 'semi-sheltered' sectors refer to those sectors where waves have small or no effect on flooding/erosion (see Fig. 3.1).

4.1.1 Flood

The magnitude of flooding was estimated through the extreme distribution of the total water level, the storm surge, and the wave runup. The storm-induced run-up was computed by applying the formula proposed by Holman (1986), which considers the significant wave height, the wave length and the beach face slope. The semi-sheltered sectors were assumed to be influenced little or very little by wave action. Therefore, in this case, the wave run-up was not taken into account. Moreover, the Total Water Level (TWL) dataset was obtained by using deep water wave data (Fig. 3.1).

TWL time series were fitted to the G.E.V. (Generalized Extreme Value) distribution using annual maxima values. The analysis was carried out in IH-AMEVA (IH-Cantabria, 2013), and the extreme water levels associated to return periods of 10 (T10) and 50 (T50) years were used to characterize different scenarios.

The area potentially flooded by those extreme events was delineated by using the bathtub approach, which consists in assuming that all areas connected to the sea with an elevation below the TWL will be flooded (Viavattene et al., 2018). In the geographic information system (GIS) environment, the outlined surface was computed for each sector, considering the beach topography and the corresponding water level for the selected return periods. Finally, a simple rectangle generated from the maximum flood potential in each sector was used to illustrate the potential 'hazard extent' (according to the terminology adopted by the RISC-KIT assessment framework; Viavattene et al., 2015).

4.1.2 Erosion

Erosion was assessed in the exposed areas using the model of Kriebel and Dean (1993). This model proposes an adaptation of the Bruun rule (1954) to estimate the changes in the beach profile due to storm waves, and the respective coastline retreat/advance. The maximum potential retreat ($R\infty$) is expressed by Bruun (1954) as (Equations 4.3 and 4.4):

$$R_\infty = \frac{S\,X_b}{B+hb-{}^{S}/_{2}}\ , \quad (4.3)$$

$$X_b = \left(\frac{h_b}{A}\right)^{3/2}, \quad (4.4)$$

where *S* is the water level variation, *hb* is the wave-breaking depth, *B* is the frontal dune height, X_b is the distance from the wave-breaking depth and *A* is the parameter related to the sediment size that characterizes the profile slope.

According to Kriebel and Dean (1993), as the beach profile changes obtained from Brunn's model represent a slow response to the water level variation, a proportional and rapid retreat due to storms must be determined taking into account the characteristic time scale of the exponential response (*Ts*) and the storm duration (*TD*). Ts was computed with equation 4.5, whereas *TD* was assumed to be the typical storm duration in the study area, a value obtained from the literature (see Table 1).

$$T_S = \frac{320xH_b^{\frac{3}{2}}}{A^3 g^{1/2}\left(1+\frac{h_b}{B}+\frac{mx_b}{h_b}\right)}, \quad (4.5)$$

Where *Hb* is the wave-breaking height; *g* is the gravitational acceleration; and *m* is the beach profile slope.

Finally, the proportional retreat (*R)* over time *(t)* was calculated from the maximum potential retreat (*R*∞) as a function of β (the ratio between the erosion time scale and the storm duration) (Equations 4.6, 4.7 and 4.8):

$$\frac{R(t)}{R_\infty} = \frac{1}{2}\left\{1 - \frac{\beta^2}{1+\beta^2} exp\left(\frac{-2\sigma t}{\beta}\right) - \frac{1}{1+\beta^2}[cos(2\sigma t) + \beta sin(2\sigma t)]\right\}, \quad (4.6)$$

$$\beta = 2\pi \frac{T_S}{T_D}, \quad (4.7)$$

$$\sigma = \frac{\pi}{T_D}. \quad (4.8)$$

Data used to compute the shoreline retreat are shown in table 1. The biggest challenge to applying the chosen empirical model was the scarcity of detailed topography and bathymetry data on a regional scale, which allows the extraction of parameters related to the morphodynamics of sandy beaches, such as the depth of closure and the beach profile slope.

Therefore, these parameters were estimated empirically according to the following simplifications: first, the depth of closure was computed using the formula proposed by Hallermeier (1978). For this purpose, nearshore wave data were extracted from the GOST database at a depth of 15 m, positioned in front of the exposed sectors (see Fig. 3.1). Afterwards, the cross-shore distance from the shoreline was obtained through Dean's equilibrium profile equation (1977). The parameter that defines the profile slope (*A*) required in this stage was estimated according to the empirical approach proposed by Dean (1987), considering k = 0.51. Finally, the beach profile slope was computed using trigonometric relations between the deep of closure and its respective distance from the coast.

The breaking-wave height (*Hb*) and break-wave depth (*hb*) time series were also obtained empirically by employing the formula proposed by Komar and Gaughan (1972) and Weggel (1972), respectively. Furthermore, in specific situations of erosion hazard in the absence of dunes, the dune height (0 m in this case) was set to 0.2 m, to allow a hazard assessment.

The computed time series of shoreline retreat were fitted to a G.E.V. function, and the values associated with the selected return periods were obtained. The hazard extent was outlined by a 50 m buffer zone from the maximum shoreline retreat in each scenario. The buffer value, first proposed by Mazzer et al. (2008), was chosen on the basis of the minimum-security distance considered by the ORLA project (MMA, 2004) for management purposes along the entire Brazilian coast.

Table 1. Data used to compute the storm-induced shoreline retreat.

Data	Source	Range of values for the exposed sectors
Frontal dune height (*B*)	RIMPEEX-Sul Project (Bonetti et al., 2018)	0.2–4.0 (m)
and sediment sizes (D_{50})		0.17–1.36 (mm)
Beach-profile slope (*m*)	trigonometric relations	0.01–0.06 (rad)
Parameter governing the profile steepness (*A*)	empirical approach (Dean, 1987)	0.09–0.23
Breaking-wave height (*Hb*)	empirical approaches: Komar and Gaughan (1973) and Weggel (1972)	6.4–7.2 (m)
Break-wave depth (*hb*)		6.1 – 8.4 (m)
Water-level variation (*S*)	TWL computed for each scenario	1.7 – 6.6 (m)
Storm duration (*TD*)	Piçarras Project (Dalinghaus et al., 2015)	192 (hours)

4.1.3 Hazard-impact indicator (i_h)

The hazard-impact indicator was attributed individually for each hazard and each sector along the coast. To obtain the flood-impact indicator, the maximum extent of the flooding scenario was subtracted from the corresponding beach width. The resulting extent was then scored as shown in table 2. Negative values indicate areas where the extent of flooding is restricted to the beach; therefore, the hazard index is null. Positive values indicate areas where the TWL exceeds the backshore, and the hazard-impact indicator increases progressively with extent of enlargement.

Table 2. Classification of the hazard-impact indicators (i_h) according to the intervals of flooding/erosion extent

Extent of flooding T10 and T50 (m)	Extent of erosion T10 (m)	Extent of erosion T50 (m)	Hazard-impact indicator
–20–0.0	0.0–0.2	0.0–19.2	0
0.0–100	0.2–0.4	19.2–41.5	1
100–200	0.4–0.7	41.5–54.8	2
200–300	0.7–1.4	54.8–70.6	3
300–400	1.4–3.4	70.6–126.3	4
>400	>3.4	>126.3	5

The erosion-impact indicator was attributed by ranking the shoreline retreat values (see table 2). This time, scores were assigned differently for T10 and T50 due to discrepancies between the ranges of values. The Natural Breaks segmentation method (Jenks and Caspall, 1971) was used to obtain the categorization in each scenario.

4.2 COASTAL EXPOSURE ASSESSMENT

The exposure analysis consisted of determining a General Exposure Indicator (I_{exp}), which is composed of different types of receptors: Land Use (LU), Social Vulnerability (SV), Transport System (TS), Business (BU) and Utilities (UT). The I_{exp} is estimated by (equation 4.9):

$$I_{exp} = (i_1 * i_2 * \dots i_n)^{1/n}, \qquad (4.9)$$

Where n is the number of the considered types of receptors.

The exposure assessment was carried out individually for each hazard impact and scenario. The five exposure categories were evaluated according to specific methods as described in this section, then ranked from 1 to 5 (None or Very Low, Low, Medium, High and Very High) before the overall integration. In the same way, the I_{exp} was scored into five categories and then reclassified from 1 to 5. The obtained values are registered in Annex C (Supplementary material).

4.2.1 Land Use (iexp_LU)

This indicator measures the relative exposure of different land uses along the coast, considering the area and the importance of the land use class for human activities. Based on the scale developed by Perini et al. (2016), each class received a representative value from 1 to 4. Therefore, areas with a high degree of human activity, such as urban settlements and croplands, were considered critical and received higher exposure values (4 and 3), while areas with little or no human activity such as sandy beaches, dunes, forests and mangroves received lower exposure values (2 and 1). Details are presented in in Supplementary Material, Annex D.

In each sector, the land use indicator was estimated according to (equation 4.10):

$$I_{\exp\_LU} = \sum_i^n \frac{V * A_i}{A_t}, \qquad (4.10)$$

Where V is the value assigned to the class, Ai, the area occupied by the class and At, the total area of the sector.

4.2.2 Social Vulnerability (iexp_SV)

The Social Vulnerability exposure indicator (iexp_SV) measures the relative exposure of different communities along the coast, considering their socio-economic characteristics according to the most common indicators used in the literature (Lima and Bonetti, 2020). The iexp_SV was computed on the basis of a Social Vulnerability Index (SVI) built for the Santa Catarina Central Sector. To build the SVI, six components were considered, as presented in table 3.

Table 3. Components used to construct the SVI

Categories	Components
Financial deprivation	Percentage of households living in poverty (A_{sv})
	Per capita income (B_{sv})
Education	Percentage of literate household heads (C_{sv})
Household structure	Number of residents per household (D_{sv})

Gender	Percentage of households headed by young women (E_{sv})
Age	Vulnerable age group (F_{sv})

In order to enable the integration of components, the values obtained were standardized, and the SVI was determined following the approach proposed by Tapsell et al. (2002). The original equation was adapted to summarize the four chosen categories (see table 3): financial deprivation, education, household structure, gender and age (equation 4.11).

$$SVI = 0.5(A_{sv} + B_{sv}) + C_{sv} + D_{sv} + E_{sv} + F_{sv} \qquad (4.11)$$

Finally, to compute the iexp_SV, the procedure described in item 4.2.1 (Equation 4.10) was performed.

4.2.3 Transport system (iexp_TS), Business (iexp_BU) and Utilities (iexp_UT)

These indicators are considered to better represent the exposure of structures, which can lead to systemic impacts or to a higher order of losses. Each one was represented by points in a GIS environment and quantified at the sectorial level with the Spatial Join resource. They were subsequently computed in terms of density, dividing the number of points by the total area of the sector.

The transport system indicator was estimated as the density of roads and local road networks in each sector. The business indicator was determined accounting for the number of establishments linked to commercial, industrial and agricultural activities in each sector, and finally, the utility indicator was defined by the number of health (hospital and clinics) and education units in the area of the hazard impact extent. Other utilities suggested by CRAF1 methodology (e.g. drinking water intake and electrical transmission substations) were not observed within the extent of the hazard areas.

4.3 IDENTIFICATION OF HOTSPOT AREAS

Hotspots were identified through application of the Coastal Index, which was computed for each hazard impact and each associated return period. The relation between the hazard impact indicator (i_h) and the general exposure indicator (I_{exp}) was established following equation 1. A sector was considered critical when CI was higher than 3.2, as this value is obtained exclusively by the combination of medium to very high indicators (Viavattene et al., 2018). The CI values were, accordingly, classified into 5 categories (None or Very Low, Low, Medium, High and Very High) to allow a qualitative representation of the hotspots along the area.

5 RESULTS

The results of the risk analysis are presented in the next sections. Flood and erosion risk assessment are addressed separately, followed by an analysis of the interaction between the two.

5.1 STORM-INDUCED FLOOD RISK ASSESSMENT

Table 4 shows the TWL for the 10- and 50-year return periods (T10 and T50, respectively) of the exposed sectors in the different municipalities of the study area. In exposed sectors, TWL varied from 2.3 to 6.6 m for T10 and from 2.5 to 7.2 m for T50. In semi-sheltered sectors, the TWL varied from 1.2 to 1.3 m, considering both scenarios. The highest levels occurred in areas reached by higher wave energy and steeper beach slopes in Tijucas and Florianópolis (Table 4). It must be highlighted that Tijucas is, in fact, particularly susceptible to the occurrence of extensive flood episodes (Santos and Bonetti, 2018), since a relatively well-developed low-lying chenier coastal plain is established on its hinterland (FitzGerald et al., 2007).

Table 4. Computed values of TWL for exposed sectors in the different municipalities of Santa Catarina Central Coast

Municipalities with exposed sectors	TWL T10			TWL T50		
	max	min	mean	max	min	mean
Tijucas	6.6	4.9	5.7	7.2	5.4	6.3
Gov. Celso Ramos	4.4	2.6	3.4	4.7	2.8	3.7
Florianópolis	6.4	2.3	3.9	7.0	2.5	4.3
Palhoça	4.4	2.3	3.4	4.8	2.5	3.7
Whole Central Coast	6.6	2.3	3.9	7.2	2.5	4.2

The flood hazard indicator in the T10 and T50 return periods is illustrated in Fig. 5.3A and Fig. 5.4A, respectively. The results show that, considering the longer return period, the hazard level in approximately 55% of the sectors lies within classes 1 and 2. Still, the classes of high and very high susceptibility (4 and 5) were representative, corresponding 32.5% of the sectors for T50. In an analysis of the differences between the T10 and T50 scenarios, an increase in hotspots was observed in the most populated city, Florianópolis.

The main flood-prone sectors, considering both scenarios, comprised the following beaches (Fig. 5.3A and 5.4A): Tijucas, Palmas, Daniela, Canasvieiras, Cachoeira do Bom Jesus, Ponta das Canas, Ingleses, Moçambique-Barra da Lagoa, Campeche, Armação and Pinheira. Higher values of i_h were concentrated in Tijucas and Florianópolis municipalities: both sites included up to 78% of the most hazardous sectors (levels 4 and 5) in T50. Also, in this case, Gov. Celso Ramos was the municipality with lower i_h values (more than 73% of its total sectors belonged to the very low and low-level classes, 1 and 2).

The flood-related exposure indices are shown in Fig. 5.3B and 5.4B. The study area exhibits large variability related to the degree of occupation (iexp_LU), with the very-high exposure class (5) predominating, followed by the low and high categories (2 and 4). Notably, most sectors that present very high levels of LU exposure are concentrated in the Gov. Celso Ramos municipality and the north of Santa Catarina Island. High values are mainly related to the presence of urban settlements close or very close to the shore.

The Social Vulnerability Indicator (iexp_VS) presented higher exposure rates in the northern sectors of Tijucas, and east of Santa Catarina Island. The very-high exposure class included the municipality of Tijucas and points located on Florianópolis beaches. Notably, categories that contributed the most to the very high values were 'per capita income', 'vulnerable age group' and 'number of residents per household'. The high-exposure class (4) predominated in Tijucas and Governador Celso Ramos municipalities. In the T50 scenario, low to intermediate values characterized most of the stretches, predominating the medium class (3) for approximately 35% of the sectors, followed by the class of low social vulnerability (2), which represented 30%.

Considering the transport system (Fig. 5.3B and 5.4B), the results showed that most of the sectors presented very low exposure of their transport network: considering the longer return period, only 13.2% were marked by very high exposure and were mainly concentrated in the Florianópolis and Gov. Celso Ramos municipalities, which pointed to a higher density of TS close to the shore in these locations. The predominance of very low exposure in the area can be explained by the absence of infrastructure near the shoreline. Still, it was possible to identify those areas where the transport system could be affected.

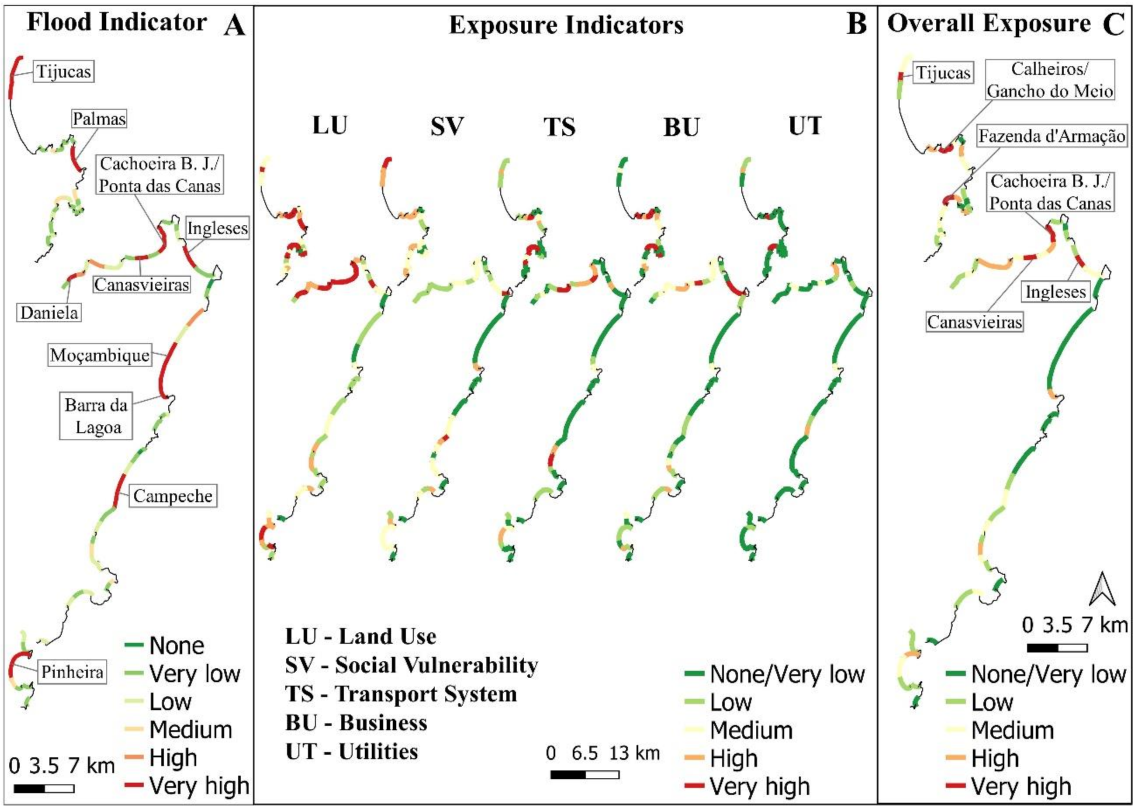

Fig. 5.3 (A) Flood impact and (B; C) exposure indicators for T10

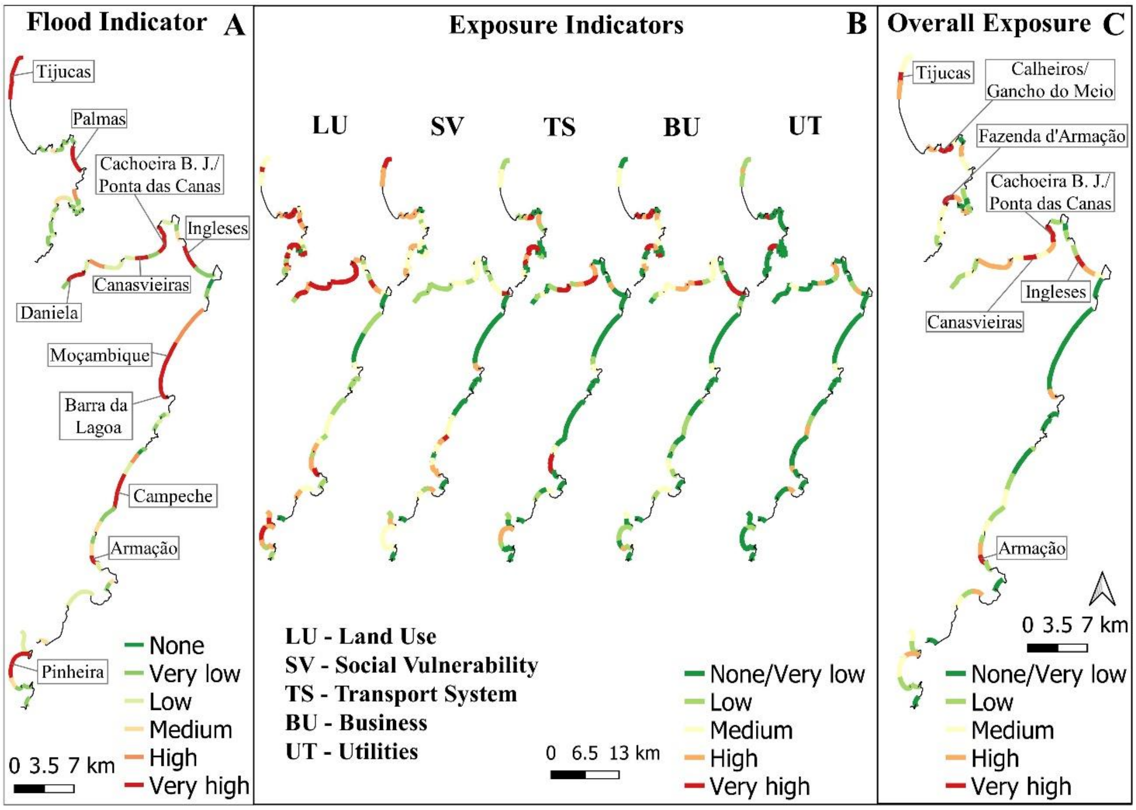

Fig. 5.4 (A) Flood impact and (B; C) exposure indicators for T50

The Business indicator was mostly represented by units linked to commerce, followed by entities related to the industry. Considering the T50 scenario, 10.8% of the sectors were characterized by very high exposure (class 5), mostly in the municipality of Gov. Celso Ramos, and the northern portion of Santa Catarina Island. Low and very low exposures were dominant when considering both return periods, accounting for up to 60% of the sectors.

The utility indicator was restricted in the study area: 80% of the sectors presented a very low exposure class, considering the maximum hazard extent. This was also mainly due to the absence of large infrastructure networks close to the shore. The very high exposure class was concentrated exclusively in the municipality of Gov. Celso Ramos. High classes (4) also appeared in the municipalities of Tijucas and Florianópolis. There was a significant number of educational units close to the shore, which were mainly represented by municipal elementary schools. Health units were rarer within the considered area and were mostly represented by small medical centres.

The overall exposure index (I_{exp}) is presented in Figs. 5.3C and 5.4C. Categories of Low and Very Low exposure were predominant in the study area, covering up to 57% of the sectors, highlighting that many of the exposure indicators used, especially those that were linked to urban infrastructure exposure, are not highly represented close to the shore.

Nonetheless, eight sectors were considered extremely critical in the higher return period, with high and very high classes of coastal exposure representing 20.4% of the total sectors for T10 and 25.3% for T50. The extremely critical sectors included the following beaches (Figs. 5.3C and 5.4C): Tijucas, Calheiros, Gancho do Meio, Fazenda d'Armação, Canasvieiras, Ponta das Canas, Ingleses and Armação.

The municipalities of Tijucas and Governador Celso Ramos were predominantly characterized by the medium exposure class; however, they had the highest percentages of classes 4 and 5, when compared with other locations. The municipality of Florianópolis presented a very heterogeneous distribution of exposure values, with the predominance of very low and low exposure in both scenarios. Still, 22.4% of its sectors are represented by classes 4 (high) and 5 (very high) in the T50 return period, which are concentrated mainly on semi-sheltered locations at the north end of the Island. In the municipality of Palhoça, the low exposure class predominates, with only 12.5% of the sectors classified as high exposure for both scenarios.

The results of the flood risk analysis are represented by the Coastal Index shown in Fig. 5.5. The computed indices varied from 0 to 5, and sectors with CI greater than 3.2 were considered critical.

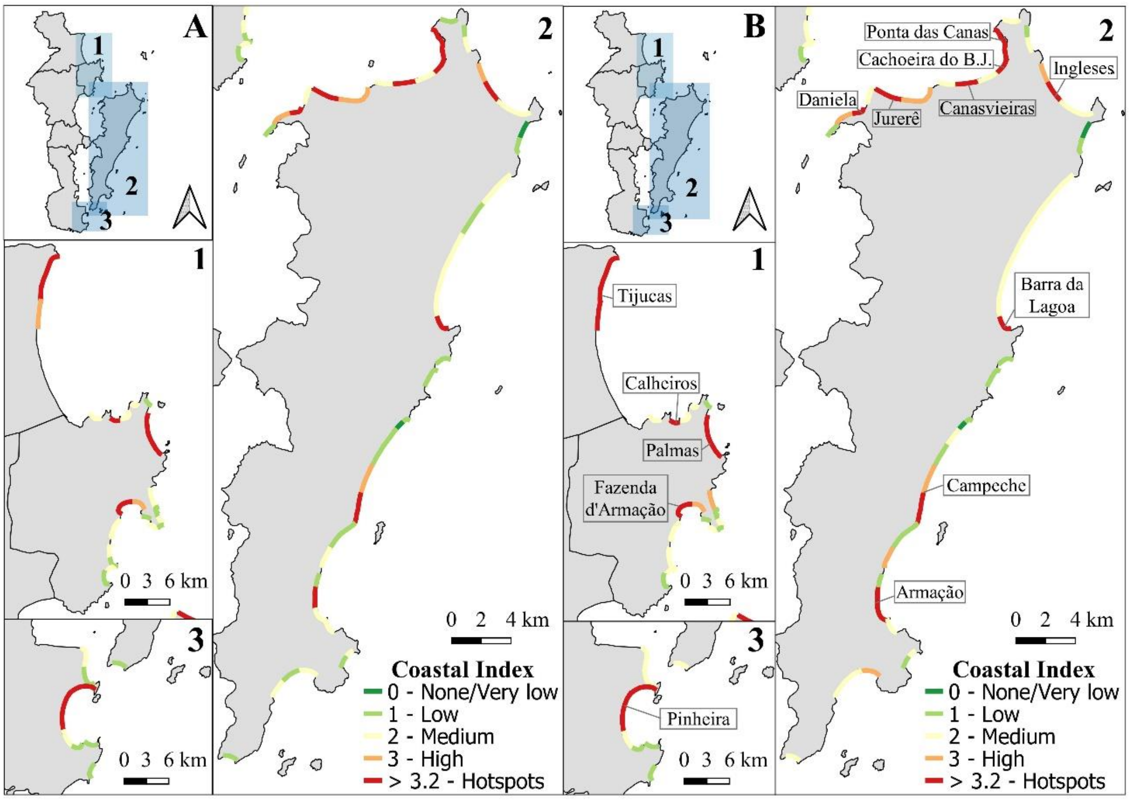

Fig. 5.5 Flood Coastal Index in T10 (A) and T50 (B) scenarios

The analysis identified 18 critical segments for T10 and 20 for T50, and the study area presented a CI average of up to 2.4. The segments considered to be at very high risk of flooding included the beaches of Tijucas, Palmas, Calheiros, Fazenda d'Armação, Daniela, Jurerê Internacional, Canasvieiras, Cachoeira do Bom Jesus, Ponta das Canas, Ingleses, Barra da Lagoa, Campeche, Armação and Pinheira (northern region) (Fig. 5.5).

It was observed that the critical sectors from exposed and semi-sheltered stretches presented different characteristics: the exposed ones were characterized by dune heights ranging from 0 to 2 m, mostly with TWL values above the average (4.2 m) and short to medium beach width (22 m average), including consolidated and slightly urbanized shores. The semi-sheltered sectors presented lower TWL (usually lower than 1.3 m); however, their backshore characteristics complicated the dissipation of storms. These sectors presented higher exposure rates combined with a short beach width (13 m average) and the absence of natural protection (dune height ranging from 0 to 1 m). Moreover, the semi-sheltered sectors characterized as critical included urbanized fringes.

The very-high-risk class represented 24% of the total sectors analysed in the longer return period scenario. The municipality of Florianópolis showed the highest flooding risk for both return periods, comprising up to 50% of the critical sectors. The municipality of Tijucas also stood out for the concentration of extreme values with a CI average of up to 4.4 and the totality of its sectors classified as very high-risk in T50 (see Fig. 5.5B). Low to medium risk classes predominated in GCR and Palhoça.

In addition, there were no significant changes in critical sectors between T10 and T50: the hotspots increased only on the Tijucas and Armação beaches. However, a considerable number of segments showed an increase in the flood risk level to a high flooding risk in the municipalities of Florianópolis and Governador Celso Ramos in the longer return period scenario.

5.2 STORM-INDUCED EROSION RISK ASSESSMENT

Values of shoreline retreat varied from 0.12 to 4.87 m in the T10 scenario and from 12.76 to 206.8 m in the T50 scenario. The highest scores were found in the Florianópolis and Tijucas municipalities, which also had the largest retraction average in the studied area (Table 5).

Table 5. Computed values of shoreline retreat in the different municipalities of Santa Catarina Central Coast

Municipalities with exposed sectors	Rt T10			Rt T50		
	max	min	mean	max	min	mean
Tijucas	4.8	1.2	3.0	181.2	91.0	121.6
Gov. Celso Ramos	0.7	0.2	0.4	67.5	26.3	45.2
Florianópolis	3.4	0.1	1.0	206.8	12.7	72.5
Palhoça	0.9	0.1	0.4	68.6	14.3	38.7
Whole Central Coast	4.8	0.1	1.0	206.8	12.7	69.3

The erosion indicator for the T10 and T50 return periods is illustrated in Fig. 5.6A and 5.7A. Under the T50 scenario, approximately 58% of the sectors presented null to low hazards. Classes 4 and 5 represented 21.5% of the analysed sectors for T10 and 29.4% for T50.

The highlighted erosion-prone sectors comprised the following beaches: Tijucas, Ingleses, Barra da Lagoa, Galheta, Joaquina, Campeche, Armação, Matadeiro and Lagoinha do Leste (see Figs. 5.6A and 5.7A). The critical stretches were concentrated in the municipalities of Tijucas and Florianópolis, indicating that these locations were more susceptible to erosion. The least susceptible district was Palhoça, in which greater than 75% of sectors had null and very low classes in both scenarios. Moreover, urban or slightly urbanized coastal segments represented approximately 66% of the highest scoring sectors in T50. Most of them were characterized by the absence of frontal dunes and steeper beach face slopes.

Exposures to erosion impact are shown in Fig. 5.6B and 5.7B. The land use indicator was mostly characterized by the medium class, which represented 43.1% of the analysed sectors in the T50 scenario. The very high category represented up to 19.6% of the analysed stretches and was concentrated in the municipalities of Governador Celso Ramos and Florianópolis. Notably, the average beach width of these sectors was 16.5 m, with a predominantly absent dune class. High exposure values may be related to the proximity of man-made infrastructure to the shore.

The very low-exposure class was predominant when assessing the Social Vulnerability Indicator in both scenarios. The second most frequent class observed was the high-exposure class, which represented 23.5% of the sectors in T50. The very-high-exposure class was observed exclusively in the municipality of Tijucas and Florianopolis. Very high exposure rates were specifically related to the 'per capita income' and the 'number of residents per household'.

Infrastructure exposures (Transport System and Business) were the least representative in the erosion impact extent. The transport network indicator is characterized by low exposure in 47% of the sectors in the T50 scenario. The stretches that are represented by very high exposure, are distributed along Florianópolis, Tijucas and Gov. Celso Ramos municipalities.

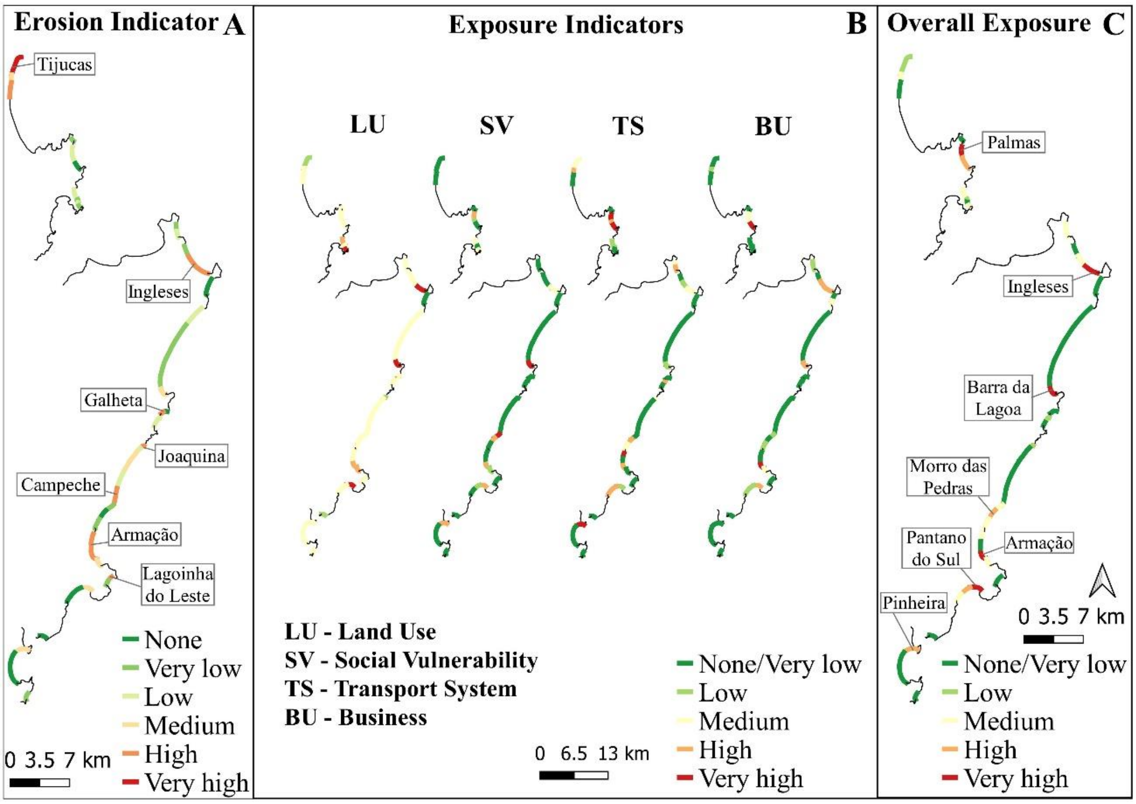

Fig. 5.6 (A) Erosion impact and (B; C) exposure indicators for T10

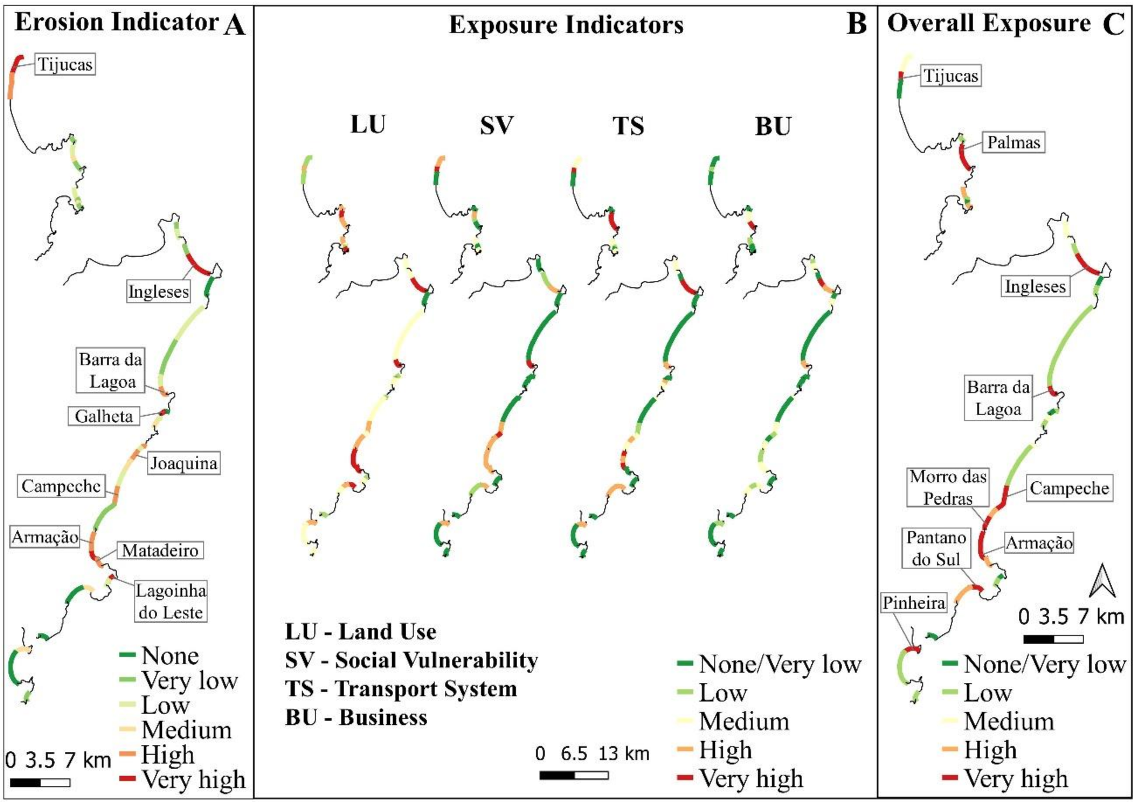

Fig. 5.7 (A) Erosion impact and (B; C) exposure indicators for T50

The Business indicator was also mostly represented by very low exposure in both return periods, T10 and T50. Up to 7.8% of the sectors are classified with high and very high iexp_BU, which points to beaches in the municipalities of Florianópolis and Governador Celso Ramos.

The overall exposure index (I_{exp}) is shown in Figs. 5.6C and 5.7C. Among the exposed sectors, the very low and low-exposure classes predominated in T10 and T50, respectively. The high- and very-high-exposure classes represented 19.5% of the total sectors for T10 and 41.1% for T50. Florianópolis presented the highest exposure indices to storm-induced erosion, comprising up to 66.6% of the sectors of high and very high classes. This municipality was followed by Governador Celso Ramos, which was characterized by beaches with reduced backshore at and a representative part of its structures very close to the coastline. The following sectors were considered extremely critical in exposures terms: Tijucas, Palmas, Ingleses, Barra da Lagoa, Campeche, Morro das Pedras, Armação, Pântano do Sul and Pinheira (Ponta do Papagaio) (see Figs. 5.6C and 5.7C).

The results of erosion risk analysis are represented by Fig. 5.8 for both scenarios. In the study area, sectors with medium risk (category 3) for return periods T10 and T50 predominated, with a CI average of up to 2.3. The very high class represents approximately 27% of the exposed segments in the T50 scenario. Moreover, among 51 sectors, only eight sectors show null erosion risk and are concentrated in the municipalities of Florianópolis and Palhoça (see Fig. 5.8B).

The analysis identified seven critical sectors for the T10 and 14 for the T50, corresponding, respectively to 13.7% and 27.4% of the stretches at very high erosion risk in the SC-CC. The hotspots were specifically located on the following beaches (Fig. 5.8B): Tijucas, Palmas, Ingleses, Barra da Lagoa, Joaquina, Campeche, Armação, Matadeiro, Pantano do Sul and Pinheira (Ponta do Papagaio). There was a large increase of critical sectors for T50 and the highlighted changes were mainly represented in the municipalities of Tijucas and Florianópolis. The high CI rates were driven by high values of exposure indicators, such as land use and transport systems, combined with medium to high values of hazard indicators. Morphologically, the critical sectors are mostly characterized by the absence of frontal dunes (78%) and a short beach width (average: 20 m). As expected, most of them are localized on Santa Catarina Island (71% in the higher return period scenario), which present

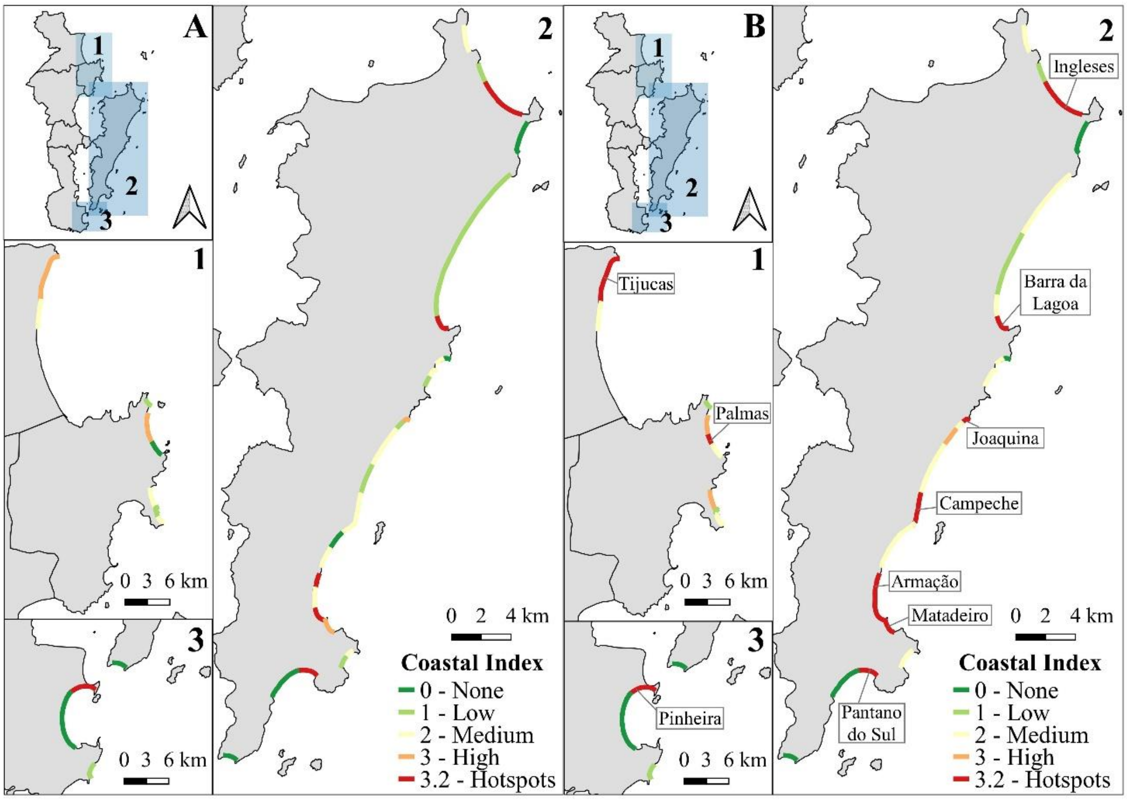

Fig. 5.8 Erosion Coastal Index in T10 (A) and T50 (B) scenarios

geographically higher exposure to hydro-meteorological events and an important urban development near the coast.

The results indicate that Florianópolis is the most susceptible and vulnerable municipality to the hazard of erosion in the study area. Considering the longer return period, middle and very high risk predominates (72%) in this city. Tijucas presents the second highest risk of erosion. With a CI average of 3.4, the risk varies from medium to very high. In the municipality of Gov. Celso Ramos, the low and medium classes predominate, while Palhoça is mainly represented by the null to low-risk categories.

5.3 CRITICAL AREAS FOR EROSION AND FLOODING HAZARDS

In the area, the hotspots that included simultaneously erosion and flooding hazards in the longer return period scenario were Tijucas, Palmas, Ingleses, Barra da Lagoa, Campeche, Armação and Pinheira (see Fig. 5.9). The highest CI values were found in the municipalities of Florianópolis and Tijucas, suggesting that they are the most susceptible and vulnerable sectors to storm-induced impacts.

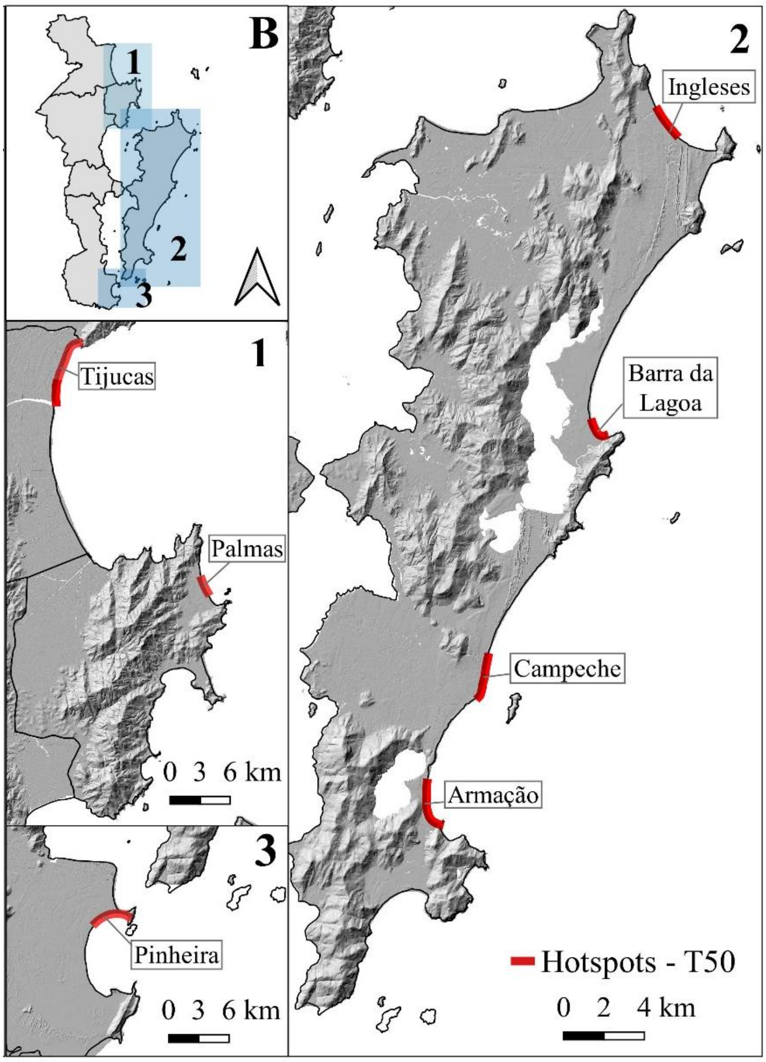

Fig. 5.9 Hotspots that may be submitted simultaneously to very high erosion and flooding hazard impacts in the longer return period scenario (50 years).

6 DISCUSSION

Integration of existing data, empirical models and spatial analysis allowed us to perform a flood and erosion risk assessment, which provided additional information concerning the area of interest. The chosen approach proved to be efficiently adaptable to data-poor areas, especially the hazard assessment module of the framework.

The high flood CI rates essentially reflected the rank of the flood impact indicators and the spatial distribution of specific exposure descriptors, such as land use and transport systems.

The higher values of the flood impact indicators can be justified by the interaction between the morphological and hydrodynamic characteristics of each sector: in general, these segments are exposed to a higher incidence of waves, with poorly developed or non-existent dunes and TWL values above the average calculated for the whole area (4.2 m). Thus, the distribution of critical sectors is mainly controlled by their geographic position, geological heritage and/or by changes linked to anthropic interference that usually is related to the removal of natural barriers (e.g. primary foredune), favouring hinterland exposure.

On the other hand, the degrees of exposure reflect the distinct patterns of urbanization and socio-economic activity in the different municipalities. Governador Celso Ramos and Florianópolis show a higher density of urban industries and infrastructure networks close to the shore, which is why a greater number of elements are exposed to the scenario proposed here. In the case of Tijucas, the most exposed sectors are essentially linked to the social vulnerability index, since it has a low-income population settled near the coastline, which is an exception in the area.

Some identified hotspots, such as the beaches of Barra da Lagoa and Armação in the municipality of Florianópolis (see Fig. 5.5B), have been highlighted previously to be under flooding and erosion threat (Bonetti et al., 2013; Klein et al., 2016b). Other examples are the beaches of Canasvieiras, Ponta das Canas, Ingleses and Campeche, which were among the most affected areas during the storms observed from 1991 to 2001 (Simó and Horn Filho, 2004). A study carried out on a smaller scale by Klein et al. (2016a) also points to the Barra da Lagoa and Ingleses beaches under a flood regime and to Ponta das Canas, Canasvieiras, Jurerê and Daniela under an overwash regime for T50 (according to the scale of flooding regime proposed by Sallenger, 2000).

Considering the analysis of the distinct probabilistic distribution, there were no major changes between scenarios. As the hazard extent was probably limited by the morphological characteristics in the study area, the exposures presented a slight increase in the higher values as well.

The superior CI rates presented in the erosion risk assessment were mostly driven by high values of exposure indicators combined with medium to high hazard categories. The exposure assessment reflected essentially the land use and the transport system descriptors, as did the flood exposure analysis. Concerning the erosion assessment, it was observed that very high retraction rates were related to very low dune height classes and short beach widths. The variables used to characterize beach morphology had the greatest influence on the results, showing the importance of using higher resolution topographic and bathymetric data to apply this approach. However, it can be noticed that the results of the hazard assessment followed the general pattern of the study area, with a retraction average for the whole area of 69.3 m for the T50 return period (Table 5). A similar value was found by Mazzer and Dillenburg (2009), which presented an average retreat of up to 70 m for some sectors in the southeast of Santa Catarina Island in a period of 64 years.

The higher risk values highlight some of the exposed beaches that have historically greater erosion problems: some critical sectors in Florianópolis, such as Ingleses, Barra da Lagoa, Joaquina, Campeche, Armação, Matadeiro and Pantano do Sul (see Fig. 5.8B), are well known areas where erosive process linked to different causes have already been described (Abreu de Castilhos et al., 1995; Castilhos and Gré, 1997; Torronteguy, 2002; Simó and Horn Filho, 2004; Faraco et al., 2006; Mazzer et al., 2008; Oliveira et al., 2008; Mazzer and Dillenburg, 2009; Rudorff and Bonetti, 2010; Bonetti et al., 2013; Klein et al., 2016b; Dalbosco et al., 2019; Leal et al., 2020)

Bonetti et al. (2018) assessed the susceptibility of sandy beaches to erosion for the entire Santa Catarina coast. The authors primarily considered environmental indicators in the analysis; thus, some results are similar to the observed pattern presented here for the erosion hazard assessment. The study pointed to the dominance of low- to medium-susceptibility values in the south sector of the state, whereas an alternated distribution of susceptibility classes, tending to higher values, prevails in the Santa Catarina Island (Florianópolis). However, differences can be seen especially in the exposed beaches of Gov. Celso Ramos and Tijucas municipalities, and they can be explained by the influence of the hydro-meteorological components on the hazard assessment. Along the Santa Catarina Coast, the inclusion of wave data has already been pointed out for having a large impact on the final result of susceptibility/vulnerability assessment (Serafim et al., 2019). Nevertheless, the primary control of the geological setting, beach orientation and proximity of man-made infrastructure over the vulnerability of the Santa Catarina coast, as previously proposed by Bonetti et al. (2018), was confirmed in our study.

The analysis of the T10 and T50 scenarios shows that the level of erosion risk tends to increase in the study area when considering a higher return period and suggests that the Santa Catarina Coast will be largely affected by coastal retreat. Furthermore, considering both hazards, the scenario tends to worsen due to the interactive relationship between the two process and the human activities on the coastal plain (Pollard et al., 2018).

In summary, the regional pattern identified for flooding and erosion risk is corroborated by the historical analysis based on the state's Civil Defence disaster databank, presented by Rudorff et al. (2014): Florianópolis is the most affected municipality in Santa Catarina State, and the other municipalities in the central sector, excepted Tijucas, have no record of emergency situations linked to storm induced-waves and surges. The authors attributed this fact to the presence of the island, which acts as a natural barrier to large wave systems, partially protecting the adjacent coast.

Tijucas is historically characterized by a low frequency of damages related to storm surges. Its coastline is located at the inner portion of a sheltered bay where wave energy is attenuated by the process of refraction and diffraction due to its morphological configuration and muddy inner shelf substrate. However, high susceptibility levels to extreme events, particularly flood, have been reported on a local scale (Santos and Bonetti, 2018). These events are concentrated in a sector where a long-term retreat of the coastline was detected by these authors based on the analysis of historical images and can be explained by the presence of low-lying areas and their greater exposure to the east waves.

The results are also partially corroborated, in a comparative way, with the analysis developed on regional scale by Serafim et al. (2019). The study highlights most of the sectors presented here as at high risk for both hazards (Fig. 5.9) (assigns high and very high scores to Palmas, Barra da Lagoa, Armação, Campeche and Pinheira beaches) and points out that most of the critical stretches are related to the low adaptive capacity found in areas with high occupational density. Similarly, here the critical sectors are driven by the high exposure indices (in turn related to high occupational density) but also by the morphological configuration, which controls the segment susceptibility to the main wave direction (as also suggested by Bonetti et al., 2018 and Mussi et al., 2018, using different scales).

The role of the morphological configuration was also discussed by Muler and Bonetti (2014), who presented a vulnerability analysis for Santa Catarina Island based on different wave directions. The study showed that, although south and southeast waves present the greatest heights, they are associated with low exposure of buildings because most of the populated sectors are located on semi-sheltered portions of the Island.

The results also highlight the key role that dunes may play in coastal protection. Dune absence or fragmentation has been related to the very high impacts of flood and erosion. In the study area, human occupation takes place over the Holocene coastal plain, represented by unconsolidated sandy sediments that offer even less protection to storm wave action. Anthropic activities in these areas contribute to the intensification of erosive processes because of the imbalance in the sediment budget of the coast, which sometimes lead to the decrease of the beach extent and presence of natural barriers, consequently making the hinterland more vulnerable to the flood events. For example, in Ingleses beach there is a natural input of sand from two dune fields that bring sediments from Santinho and Moçambique beaches (through sand overpassing). In the last decades, urban development in this sector was established over the dunes, interrupting sand transport and leading to a local deficit of sediments (Vieira da Silva et al., 2016).

It is important to notice that, although the erosion assessment was carried out only for the exposed sectors, many semi-sheltered beaches are characterized by low-land areas and presented an extremely low level of protection in face of a small TWL increase. Studies carried out in the Florianópolis region show that even considering only the sea level rise, the city has little or no protection from its effects (Montanari et al., 2020). Furthermore, for sheltered and semi-sheltered sectors, the regional pattern of beach responses to extreme events can be disrupted on a local scale due to the connectivity between beach systems via physical processes, like sediment redistribution or/and headland bypassing (Burvingt et al., 2017).

Even though the need to apply some alternatives for the treatment of the predicted variables in CRAF1, the tool proved to be flexible enough to be used in conditions of greater data scarcity. It has already been pointed out that, specifically for hazard assessment, the type of data required make it difficult to evaluate some coastal stretches at regional levels (Narra et al., 2019); however, in this study, we show that the tool can be implemented with simplifications by using some alternatives. Here, several parameters were simplified due to the low resolution of the input data; nevertheless, the general pattern was respected, corroborating the well-known areas and providing important information, especially in qualitative terms, for the Santa Catarina Central Coast.

7 CONCLUSIONS

This study applied the CRAF1 framework in a data-scarcity condition, focusing on the Santa Catarina Central Coast, to identify storm-induced hotspots of flood and erosion. The approach proved to be efficient and adaptable to sites where high-resolution data are usually unavailable. Despite the need to adopt some assumptions and simplifications, the method generated useful results for the identification of critical risk areas.

The flood and erosion hazards were estimated according to TWL and coastline retraction for T10 and T50. In the longer return period scenario, TWL pointed to an average of 4.2 m in the study area, making several sectors susceptible to damage, especially those that suffer with great wave energy action and present high values of beach face slope, such as Tijucas and Florianópolis. In addition, the storm-induced retreat indicated expressive shoreline displacement for several sectors, highlighting some of the exposed beaches that have historically greater erosion problems, such as Ingleses and Armação on Santa Catarina Island.

The hazard indicators stressed some of the well-known areas prone to the impacts of flooding and erosion. The municipalities that concentrate the most hazardous classes are Tijucas and Florianópolis. The highest scores are related to the presence of low-land areas combined with insignificant values of frontal dune heights, which make the environment more susceptible even in semi-sheltered sectors.

The exposure analysis was carried out taking into account the presence of different receptors within the delineated impact extent. The general exposure indicator showed that categories of low and very low exposure are predominant. Those of very high exposure are the least frequent and characterize the municipalities of Tijucas and Governador Celso Ramos for the impact of flooding and Florianópolis and Governador Celso Ramos for the impact of erosion. Three sectors comprising the beaches of Tijucas, Ingleses and Armação showed the highest exposure rates for both hazards. Moreover, the upper index values allowed us to determine how the exposure of a particular receptor influenced the general exposure indicator: the variables with the greatest influence on exposure levels were land use and transport system categories. Utilities was the less expressive descriptor in the area.

The integration of indicators through risk maps allowed the identification of 18 critical segments for T10 and 20 for T50 concerning flood risk. Likewise, in respect to erosion risk, where the analysed area corresponds to the exposed sectors to the main wave directions, seven critical stretches were identified for T10 and 14 for T50. In both cases, the sectors under very high risk to storm-induced impacts include the municipalities of Florianópolis and Tijucas, which correspond to the areas with the highest number of registered warning recurrences due to storm events. Among the exposed sectors, nine simultaneously presented the risk of erosion and flooding in the longer return period scenario. This result was related to the anthropic occupation of lowland areas, which are naturally more susceptible to wave impacts.

The risk analysis in probabilistic terms allowed the identification of the main hazard in the study area, showing that the storm-induced erosion process tended to be more severe along the years when compared with the flooding process. However, often these hazards are strongly related, and when considering a large return period, a major impact can reach a greater number of stretches, as the hinterland becomes more susceptible.

Some simplifications were necessary when applying the methodology, for example, to obtain geomorphological and hydraulic parameters, as well for the data used in the exposure analysis. The risk assessment also took into account the maximum hazard extent in each sector and did not consider important parameters related to overwashing processes, obstacles, soil infiltration and the presence of river basins, which may influence the regional vulnerability pattern.

Nevertheless, it was possible to identify the most critical areas, which coincide with those where damage was registered during extreme events and also with some hotspots highlighted in previous works. Although many previous studies have been developed in the area, future sea-level rise scenarios were not considered in those analyses, a factor that can be of great importance for management purposes. In this way, the results obtained here can be used as the basis for future research by indicating the areas that deserve more attention and more detailed analysis in the perspective of potential risk.

This study proposed some alternatives that allow the implementation of the CRAF1 tool conditions of data scarcity. With this, it is expected to inspire similar analyses in countries that do not have a structured spatial data infrastructure, expanding the scope of the original methodology applied in Europe.

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9 SUPPLEMENTARY MATERIAL

Annex A. Socio-economic information obtained from the IBGE census (2011)

Components	Variables extracted from the IBGE dataset	Variable interaction
A (%)	V1. Permanent private households earning up to ½ minimum wage per capita per month V2. Number of permanent private households	$\frac{V1 * 100}{V2}$
B	V3. Total monthly income of permanent private households V4. Residents in permanent private households	$\frac{V3}{V4}$
C (%)	V5. Literate household heads V6. Total number of household heads	$\frac{V5 * 100}{V6}$
D	V4	V4
E (%)	V7. Female household heads aged 29 and younger	$\frac{V7 * 100}{V6}$
F (%)	V8. Population aged 12 and younger V9. Population aged 65 and older	$\frac{(V8 + V9) * 100}{V4}$

Annex B. Level of analytical detail recommended and the simplifications realized for the CRAF1 implementation in the study area

Characteristics	Level of analytical detail	
	Recommended	**Applied**
Hazard assessment scale	Uniform sectors of 1 km length	Sector of up to 2.5 km length according to the available data.
Morphological characterization	A DTM with a fine grid and high resolution to obtain the morphological parameters and the topography to be used in the flood assessment.	A DTM with vertical resolution of 2.5 m and several limitations between the land-water surfaces.
Beach profiles	Cross-shore profiles including the submerged part as an extension of the ones obtained from the emerged beach DTM.	Field data obtained in specific locations along the emerged area and empirical relationships to obtain parameters linked to the submerged part.
Hazard model (inundation extent)	Bathtub model and overwash extent model in the case of low-lying areas.	Only the bathtub extent model
Wave and water level data	Long time series (recorded or hindcast) of wave and water level data.	A reanalysis database to provide wave and water level information in deep and

		intermediate waters. Empirical relationships to obtain wave parameters in shallow waters.
Exposure Indicators	Different sources types, but normally well actualized obtained at coarse CORINE-type scale	Different sources of information with heterogeneous scale and resolution degrees.

Annex C. Values obtained from the exposure analysis

	Flood extent					Erosion extent				
Exposure indicators / **Exposure Values**	**1** Null or Very Low	**2** Low	**3** Moderate	**4** High	**5** Very High	**1** Null or Very Low	**2** Low	**3** Moderate	**4** High	**5** Very High
Land Use	1.0-1.4	1.4-2.1	2.1-2.6	2.6-3.2	3.2-4.0	0.0-1.0	1.0-1.8	1.8-2.0	2.0-2.3	2.3-2.9
Social Vulnerability	0.0	0.0-1.2	1.2-1.6	1.6-2.2	2.2-2.7	0.0	0.0-1.2	1.2-1.4	1.4-1.9	1.9-2.4
Transport System	0.0-64	64-152	152-255	255-367	>367	0.0-9.4	9.4-24	24-77	77-142	142-240
Business	0.0-18	18-38	38-84	84-193	>193	0.0-26	26-115	115-219	219-340	>340
Utilities	0.0-0.3	0.3-1.0	1.0-1.9	1.9-4.1	4.1-9.5	–				
Overall Exposure	1.0-1.3	1.3-2.1	2.1-2.7	2.7-3.4	3.4-4.7	0.0-1.3	1.3-1.8	1.8-2.3	2.3-2.9	2.9-4.2

Annex D. Land-use classification according the scale developed by Perini et al. (2016)

Land use classes (Mussi, 2017)	Assigned values
Dense ombrophilous forest Vegetated dunes Mangroves Continental surface waters Lagoons Reforestation area Early-stage undergrowth Areas without vegetation	1
Free dunes Sandy beaches	2

Croplands	3
Urban settlements	4

LIST OF ABBREVIATIONS

Abbreviation	Full meaning
BU	Business
CI	Coastal Index
CNES	National register of health establishments
CRAF1	Coastal Risk Assessment Framework phase one
DEINFRA	Infrastructure Department of Santa Catarina' State
DHN	Directorate of Hydrography and Navigation
G.E.V.	Generalized Extreme Value
GIS	Geographic Information System
GOST	Global Ocean Surge and Tide database
IBGE	Brazilian Institute of Geography and Statistics
I_{exp}	Exposure indicator
i_h	Hazard indicator
IH-AMEVA	Mathematical and Statistical Analysis of Environmental Variables
LU	Land Use
RIMPEEX-Sul	Integrated Network for Monitoring and Forecasting Extreme Events in the Southern Region
ROW	Regional Ocean Waves database
SC-CC	Santa Catarina Central Coast
SDS	State Secretary of Sustainable Economic Development
SEAP	Special Secretariat for Aquaculture and Fisheries
SED-SC	Secretary of Education of Santa Catarina's State
SV	Social Vulnerability
SVI	Social Vulnerability Index
T	Return Period
TS	Transport System
TWL	Total Water Level
UT	Utilities

LIST OF SYMBOLS

SYMBOL	MEANING

A	Parameter governing the profile steepness
A_i	Area occupied by the land use class
A_t	Total area of the sector
B	Frontal dune height
D_{50}	Sediment sizes
g	Gravitational acceleration
Hb	Breaking wave height
hb	Break wave depth
k	Dean’s constant
m	Beach profile slope
R_∞	Maximum potential retreat
R_t	Potential retreat
S	Water level variation
TD	Storm duration
T_S	Time scale of exponential response
V	Value assigned to the land use class
X_b	Distance from the coast to the wave breaking depth
β	Ratio between the erosion time scale and the storm duration

10 CONSIDERAÇÕES FINAIS

Neste trabalho foi apresentada a aplicação da metodologia CRAF1 para identificar áreas de alto risco de inundação e erosão induzidos por eventos extremos de marés de tempestade no Setor Costeiro Central de Santa Catarina. Apesar das dificuldades de aplicação da abordagem devido à demanda de grande quantidade de dados em escala regional, a metodologia mostrou-se eficaz na medida em que identificou boa parte de setores que são reconhecidamente impactados historicamente.

Em um primeiro momento a magnitude dos processos de inundação e erosão foram estimados através de modelos empíricos. Nesta etapa foram calculadas as cotas de inundação e retração instantânea da linha de costa para os períodos de retorno de 10 e 50 anos. Os municípios onde ocorrem maiores cotas de inundação e retração da linha de costa são Florianópolis e Tijucas, sendo que os maiores índices de risco relacionam-se sobretudo a áreas de baixa topografia associadas à ausência de barreiras naturais. Nota-se que estas características tornam muitos setores susceptíveis à impactos de eventos extremos, mesmo quando não expostos diretamente à direção principal de ondas.

Ambos os resultados apresentaram certo grau de sobrestimação em relação a valores encontrados na literatura. A razão pode ser atribuída sobretudo às características dos dados de entrada, bem como à demasiada simplificação do modelo empírico utilizado em escala regional. Observa-se no entanto que os valores, quando transformados em índices, forneceram boa capacidade de distinção de setores, apontando para muitas áreas já conhecidas por seu elevado grau de susceptibilidade e corroborando o padrão regional observado em diferentes estudos.

Posteriormente foi avaliada a exposição de diferentes receptores aos efeitos considerados e construído o índice de exposição geral. Os municípios apresentaram comportamentos diferentes em relação aos dois tipos de impacto, destacando-se valores elevados de exposição em Florianópolis, Governador Celso Ramos e Tijucas, sobretudo devido aos indicadores de uso do solo e sistema de transportes. Constata-se que para a área em questão o indicador de utilidades foi pouco ou nada expressivo, tendo sido desconsiderado na análise relacionada à erosão.

A partir da integração dos índices de erosão e inundação e exposição foram obtidos os índices costeiros, que destacaram maior número de setores críticos nos municípios de Tijucas e Florianópolis. Os resultados indicam que o risco é maior quando considerado o processo de inundação, onde observa-se maior média de IC devido ao alcance que o impacto pode atingir. Contudo, quando analisados os diferentes cenários, o risco de erosão mostra a maior tendência ao aumento ao longo dos anos, podendo ser o principal agente responsável pela intensificação dos impactos já previstos a longo prazo.

Foram identificados 9 *hotspots* costeiros que apresentam risco simultâneo à inundação e erosão, sendo desejável especial atenção à estes setores por parte dos órgãos de gerenciamento costeiro. Os resultados mostram-se congruentes com registros históricos e relacionam-se sobretudo à ocupação antrópica em áreas naturalmente mais susceptíveis ao impacto de eventos extremos.

Os resultados permitem avaliar que a metodologia CRAF1 é adequada para um primeiro nível de análise e para a identificação de trechos que requerem maior atenção e prioridades de estratégia de gestão. Certamente a abordagem é limitada pela qualidade e precisão dos dados de entrada, bem como pela utilização de modelos empíricos para a análise dos impactos, contudo, ainda assim os resultados ressaltam os pontos mais sensíveis presentes na orla.

Recomenda-se para trabalhos futuros o refinamento dos dados de topografia e batimetria para uma melhor caracterização da interface continente-oceano. Além disso, recomenda-se a aplicação de modelagem numérica em escala de detalhe nos *hotspots* identificados a fim de melhorar a avaliação realizada em escala regional e reduzir a possível sobrestimação ou subestimação do risco em cada setor.

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APÊNDICE A – DADOS DE MARÉ METEOROLÓGICA E MARÉ ASTRONÔMICA UTILIZADOS E CÁLCULO DA COTA DE INUNDAÇÃO

1. Caracterização do nível de água (MM e MA)

Figura A1. Série temporal de Maré Meteorológica (a) e Maré Astronômica (b) no ponto 1 (P1)

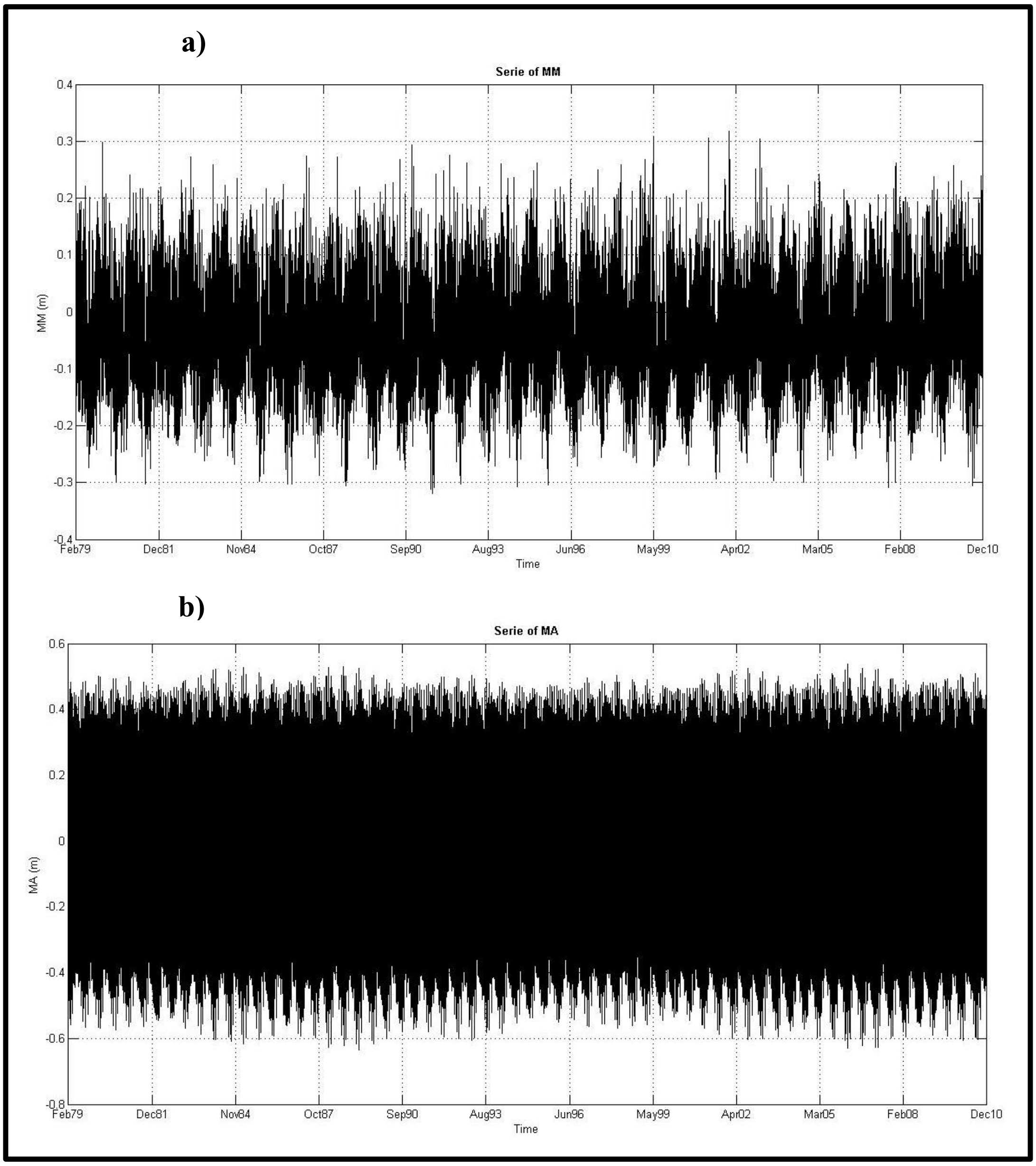
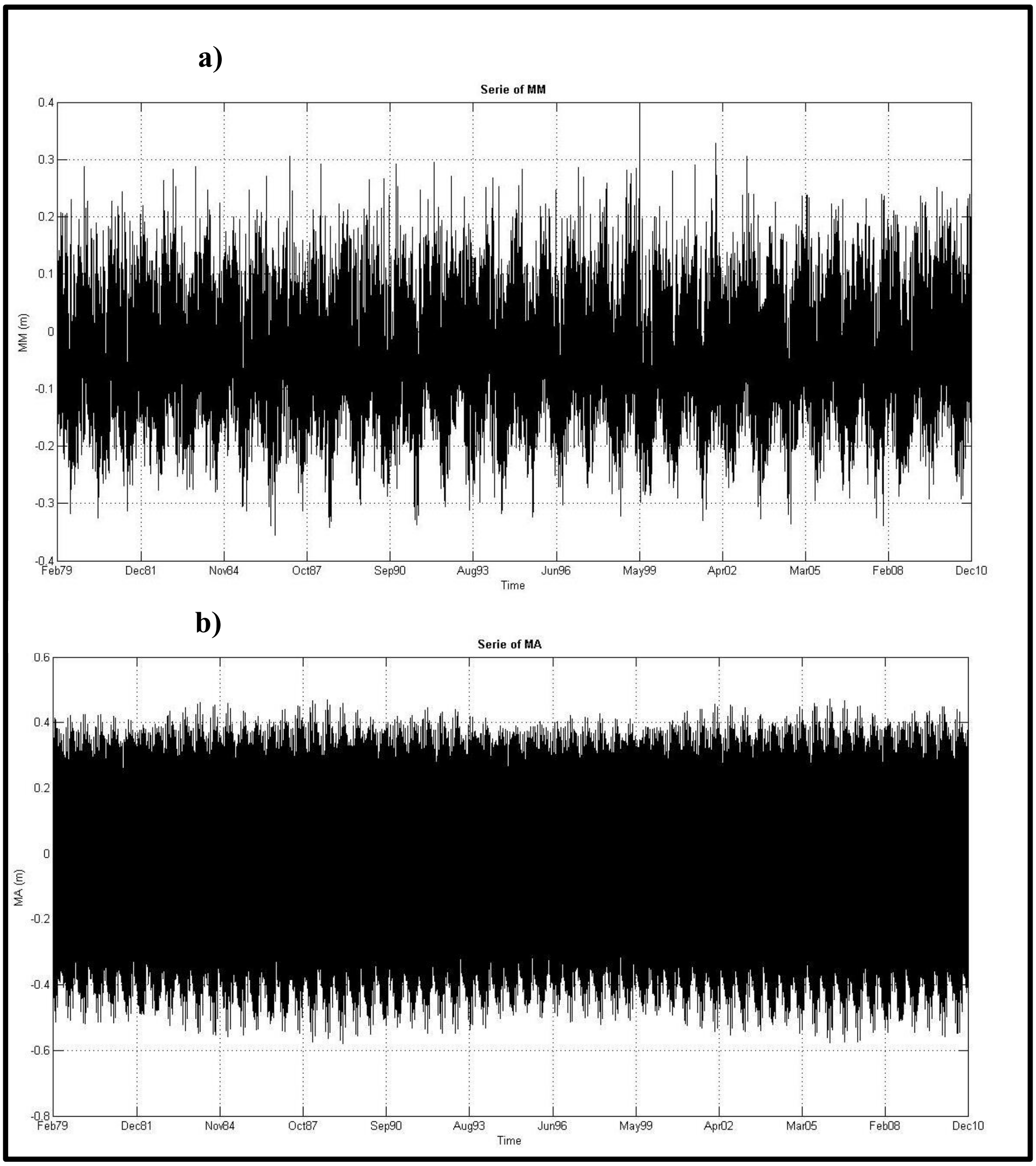


Figura A2. Série temporal de Maré Meteorológica (a) e Maré Astronômica (b) no ponto 2 (P2)



2. Cota de Inundação

Setores semi-abrigados: foram considerados no cálculo apenas a análise de extremos dos dados de Maré astronômica e Maré Meteorológica (Figura A3 e A4). Aos valores obtidos foi adicionada a diferença de datum (+0.61m). Considerou-se portanto o impacto de inundação apenas de acordo com a sobrelevação do nível do mar, com pouca ou muito pouca influência da ação de ondas.

Figura A3. Cota de Inundação - P1

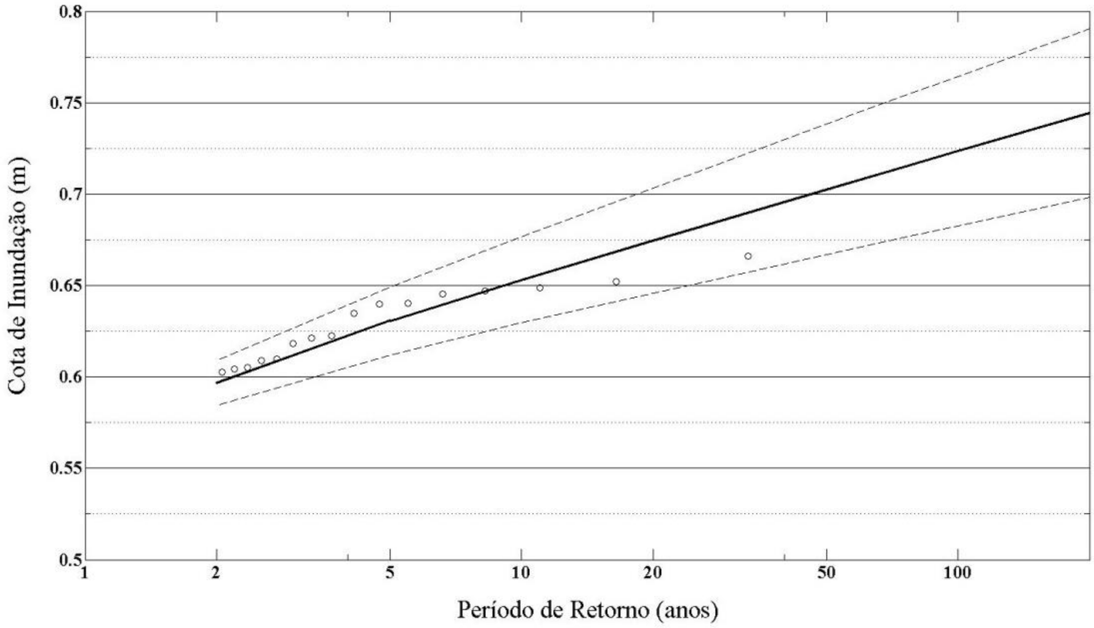
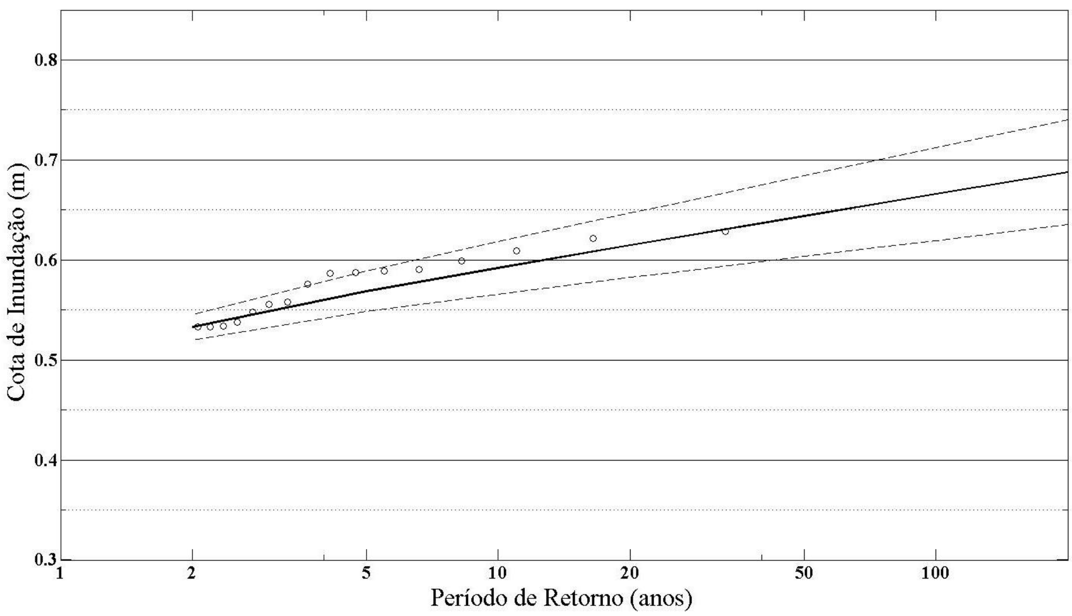


Figura A4. Cota de Inundação – P2



Setores expostos: foi considerada na análise de extremos a soma de valores de MM+MA+runup, adcionando-se posteriormente o valor de diferença de datum (+0.61m). O conjunto de dados obtidos pode ser visualizado através das Figuras A5 e A6.

Figura A5. Valores de Cota de Inundação (TWL) obtidos para o período de retorno de 10 anos (T10)

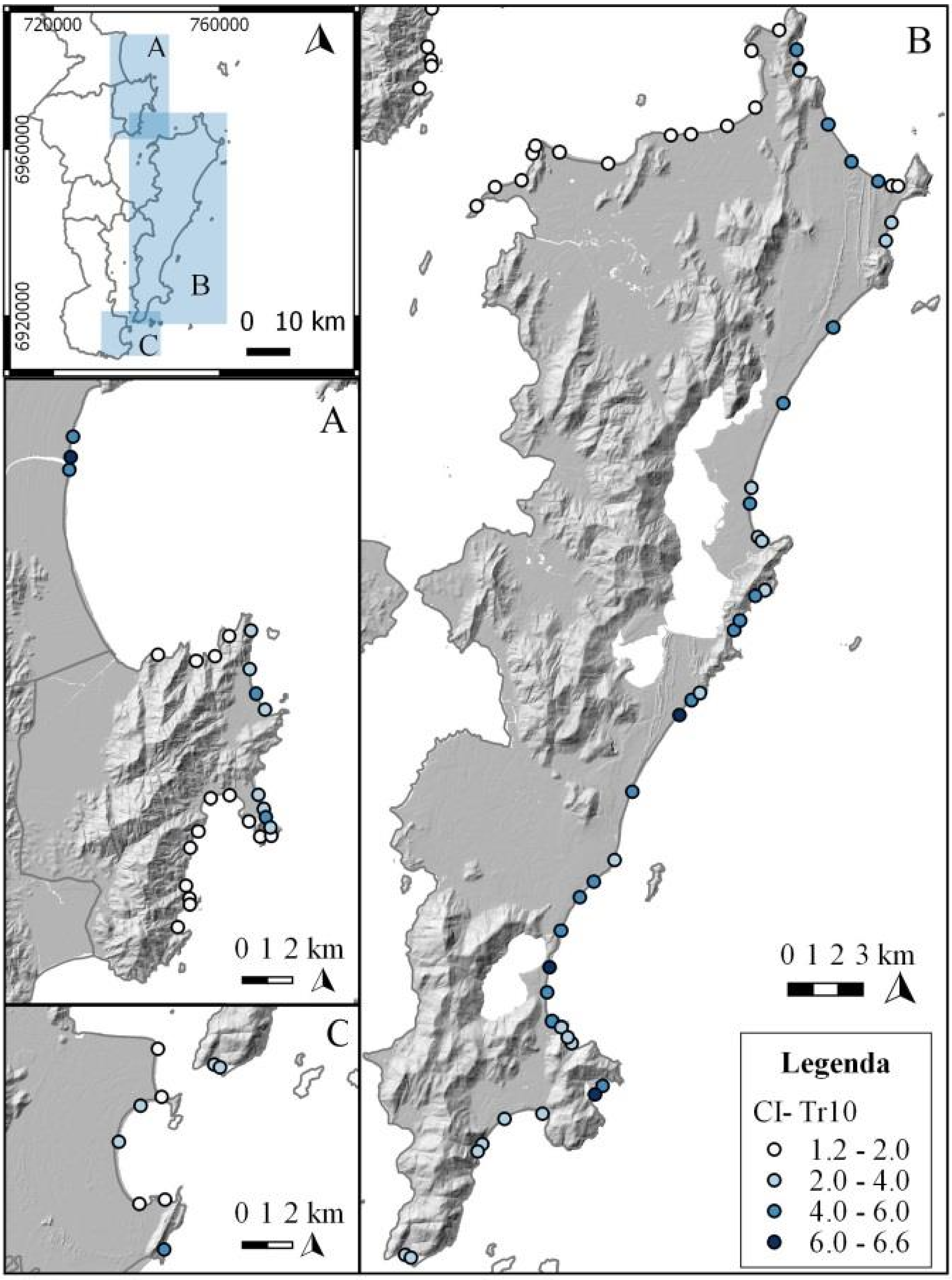
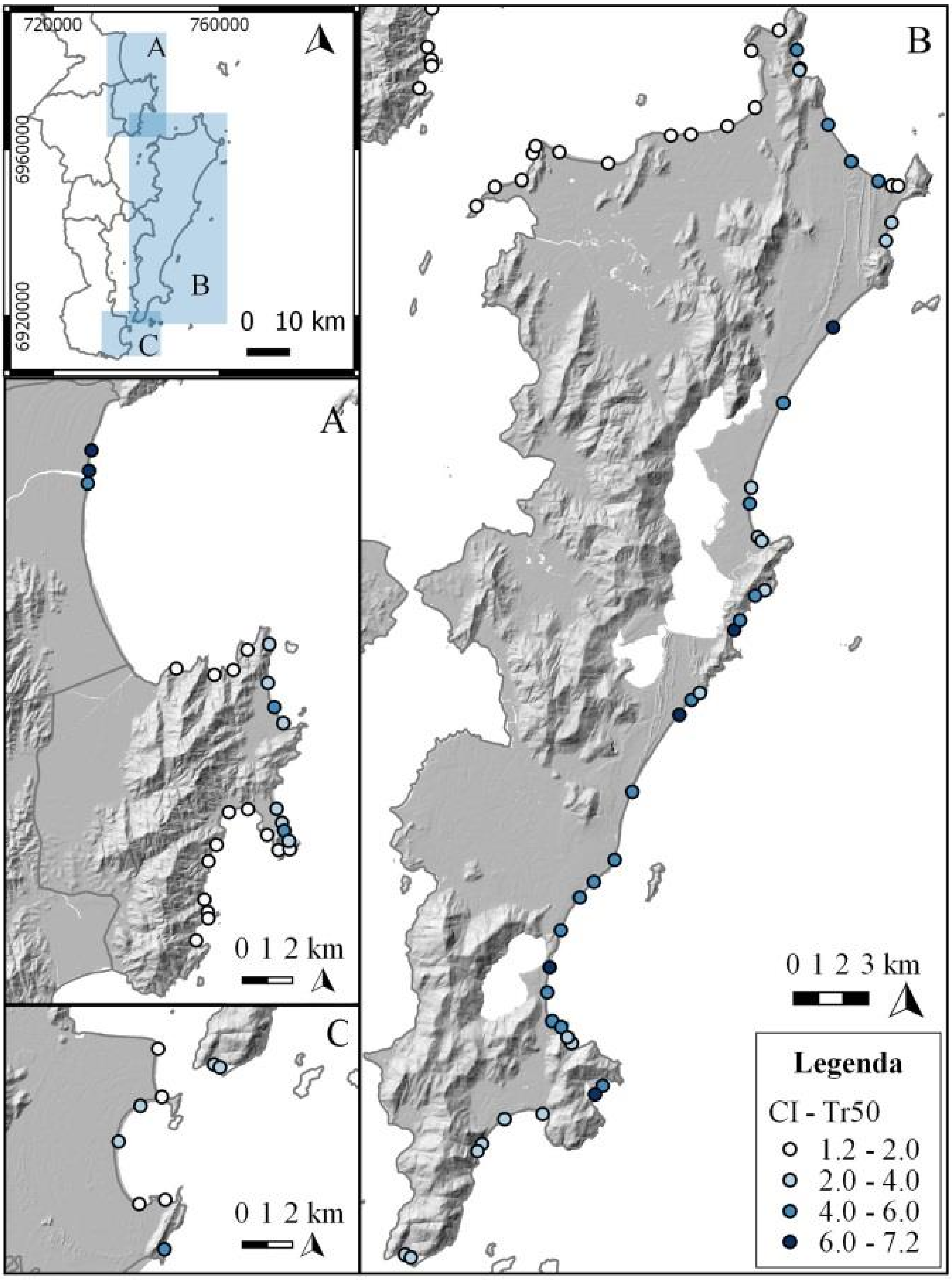


Figura A6. Valores de Cota de Inundação (TWL) obtidos para o período de retorno de 50 anos (T50)



A cota de inundação obtida em cada setor permitiu o mapeamento da extensão do impacto de inundação na área, como ilustrado pelas Figuras A7 e A8. O indicador de impacto foi construído a partir da extensão máxima encontrada em cada setor subtraída da largura da praia (de acordo com os dados do projeto RIMPEEX).

Figura A7. Extensão do impacto de inundação estimada para o período de retorno de 10 anos

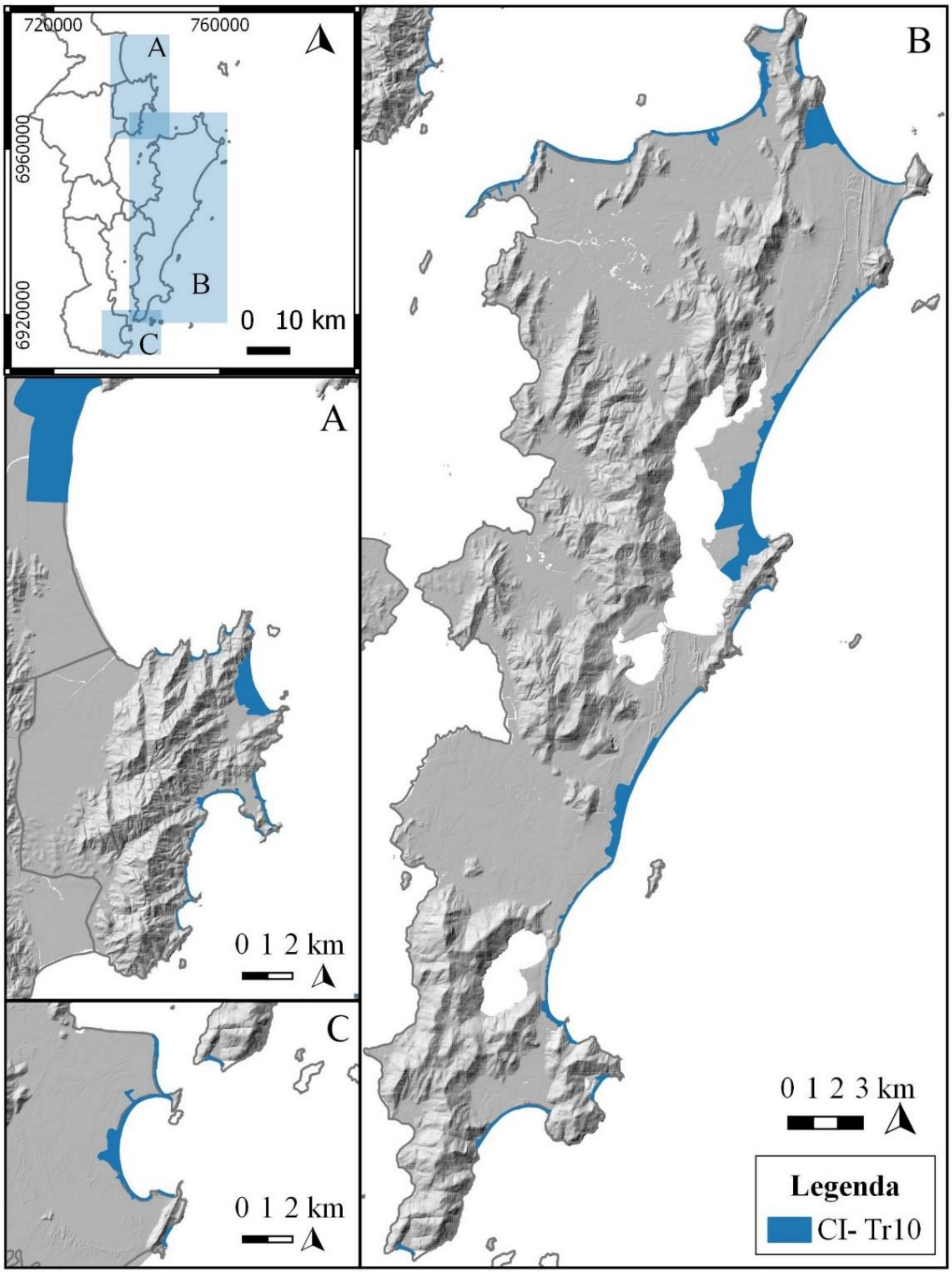
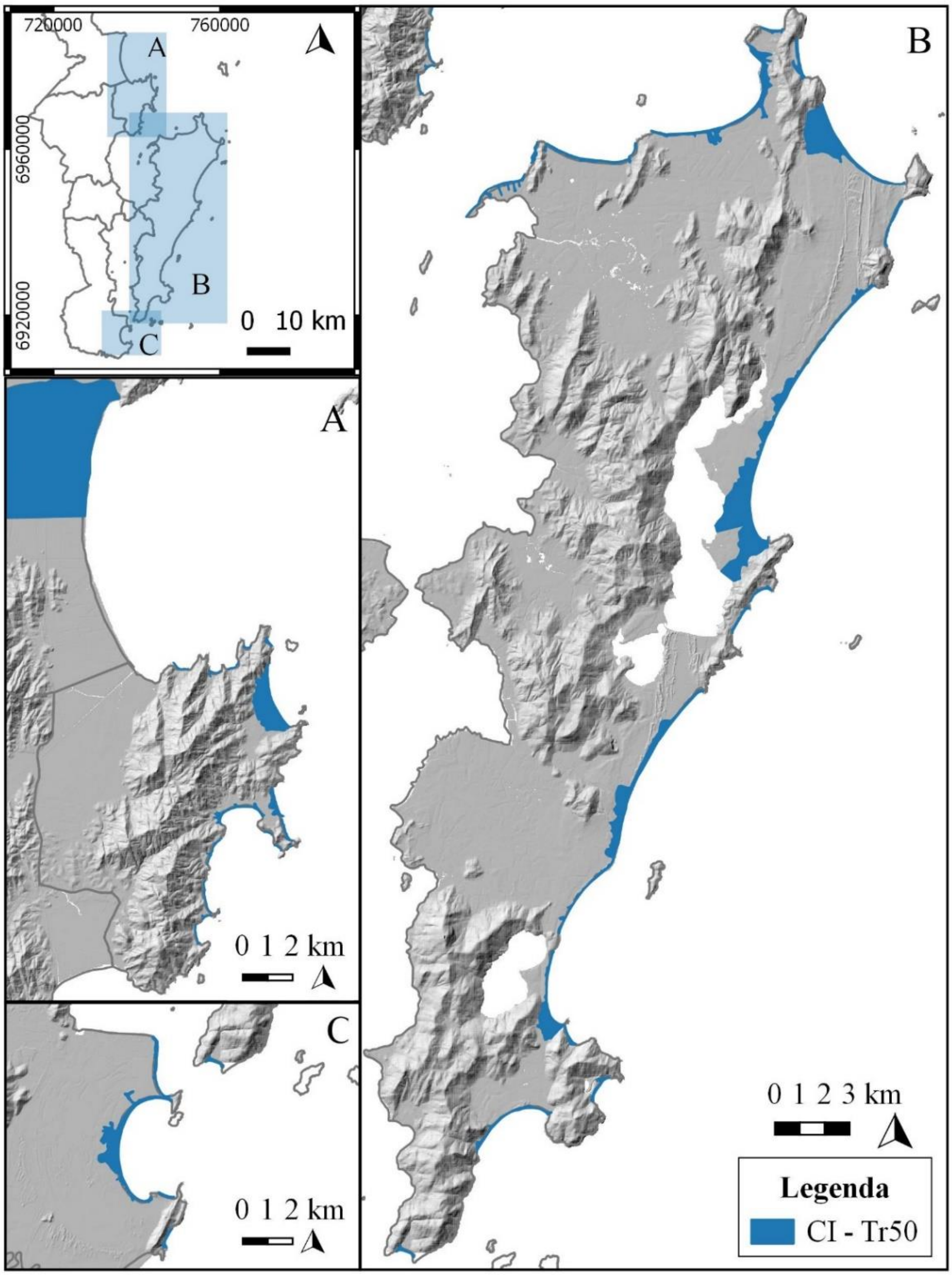


Figura A8. Extensão do impacto de inundação estimada para o período de retorno de 50 anos



APÊNDICE B – RETRAÇÃO DA LINHA DE COSTA: DADOS COMPLEMENTARES

A partir dos parâmetros de onda obtidos em frente a cada setor ou grupo de setores, chegou-se aos valores de profundidade de fechamento e declividade dos perfis praiais da área de estudo. Os resultados podem ser visualizados através da Tabela B1.

Tabela B1. Variáveis utilizadas e resultado do cálculo de profundidade de fechamento (h*) e declividade do perfil (m)

Praia	Setor N_S	A	Hs_{12}	Tp_{12}	h*	m
Tijucas	1	0,16	2,44	10,14	3,93	0,03
Tijucas	2	0,17	2,44	10,14	3,93	0,05
Tijucas	3	0,22	2,44	10,14	3,93	0,05
Praia de Fora	4	0,10	2,72	9,27	4,25	0,02
Palmas	5	0,10	2,72	9,27	4,25	0,02
Palmas	6	0,11	2,72	9,27	4,25	0,02
Palmas	7	0,10	2,72	9,27	4,25	0,02
Praia Grande	8	0,11	2,66	8,89	4,13	0,02
Bananeiras	9	0,11	2,66	8,89	4,13	0,02
Praia das Cordas	10	0,12	2,66	8,89	4,13	0,02
Cordas	11	0,11	2,66	8,89	4,13	0,03
Praia Brava	12	0,11	2,87	10,22	4,56	0,02
Praia Brava	13	0,10	2,87	10,22	4,56	0,02
Praia Brava	14	0,10	2,87	10,22	4,56	0,02
Ingleses	15	0,10	2,76	9,7	4,35	0,02
Ingleses	16	0,10	2,76	9,7	4,35	0,02
Ingleses	17	0,10	2,76	9,7	4,35	0,02
Santinho	18	0,10	3,12	11	4,99	0,02
Santinho	19	0,10	3,12	11	4,99	0,02
Mocambique	20	0,13	3,31	12,17	5,36	0,03
Mocambique	21	0,12	3,39	11,92	5,46	0,03

Mocambique	22	0,11	3,2	11,42	5,14	0,02
Mocambique	23	0,12	3,2	11,42	5,14	0,02
Barra da Lagoa	24	0,10	3,2	11,42	5,14	0,01
Barra da Lagoa	25	0,09	3,2	11,42	5,14	0,01
Praia da Galheta	26	0,10	3,1	11,43	4,99	0,02
Praia da Galheta	27	0,12	3,1	11,43	4,99	0,02
Mole	28	0,16	3,16	11,23	5,06	0,04
Mole	29	0,14	3,16	11,23	5,06	0,03
Joaquina	30	0,10	3,31	11,87	5,33	0,02
Joaquina	31	0,17	3,31	11,87	5,33	0,04
Joaquina	32	0,17	3,31	11,87	5,33	0,04
Campeche	33	0,15	2,82	11,16	4,56	0,04
Campeche	34	0,12	2,78	11,41	4,51	0,02
Morro das Pedras	35	0,13	2,89	11,79	4,70	0,04
Morro das Pedras	36	0,09	2,89	11,79	4,70	0,02
Morro das Pedras	37	0,11	2,85	11,82	4,64	0,03
Armacao	38	0,23	2,85	11,6	4,63	0,06
Armacao	39	0,23	2,85	11,6	4,63	0,05
Armacao	40	0,09	2,85	11,6	4,63	0,01
Armacao	41	0,09	2,85	11,6	4,63	0,01
Matadeiro	42	0,09	2,82	10,95	4,54	0,01
Matadeiro	43	0,09	2,82	10,95	4,54	0,02
Lagoinha do Leste	44	0,11	3,18	11,59	5,12	0,02
Lagoinha do Leste	45	0,13	3,18	11,59	5,12	0,03
Pantano do Sul	46	0,10	2,49	11,8	4,09	0,02
Pantano do Sul	47	0,11	2,49	11,8	4,09	0,03
Solidao	48	0,10	2,49	11,8	4,09	0,02
Solidao	49	0,10	2,49	11,8	4,09	0,02
Naufragados	50	0,10	2,1	11,43	3,48	0,02
Naufragados	51	0,10	2,1	11,43	3,48	0,03

Pinheira	52	0,09	3,09	12,14	5,03	0,01
Pinheira	53	0,09	3,09	12,14	5,03	0,02
Prainha da Guarda	54	0,11	2,75	12,4	4,52	0,03

O método de Convolução foi aplicado aos 54 perfis praiais calculados anteriormente para todas as praias expostas do setor costeiro central. Para tanto foram estimados também os parâmetros de altura de quebra (Hb) (Figura B1), profundidade de quebra (hb) e tempo-resposta do perfil (Ts). Os resultados podem ser visualizados na Tabela B2.

Figura B1. Parâmetros de altura de quebra calculados por zona e submetidos à análise de extremos (Zona 2 = dados extraídos do ponto P1; Zona 3= dados extraídos do ponto P2)

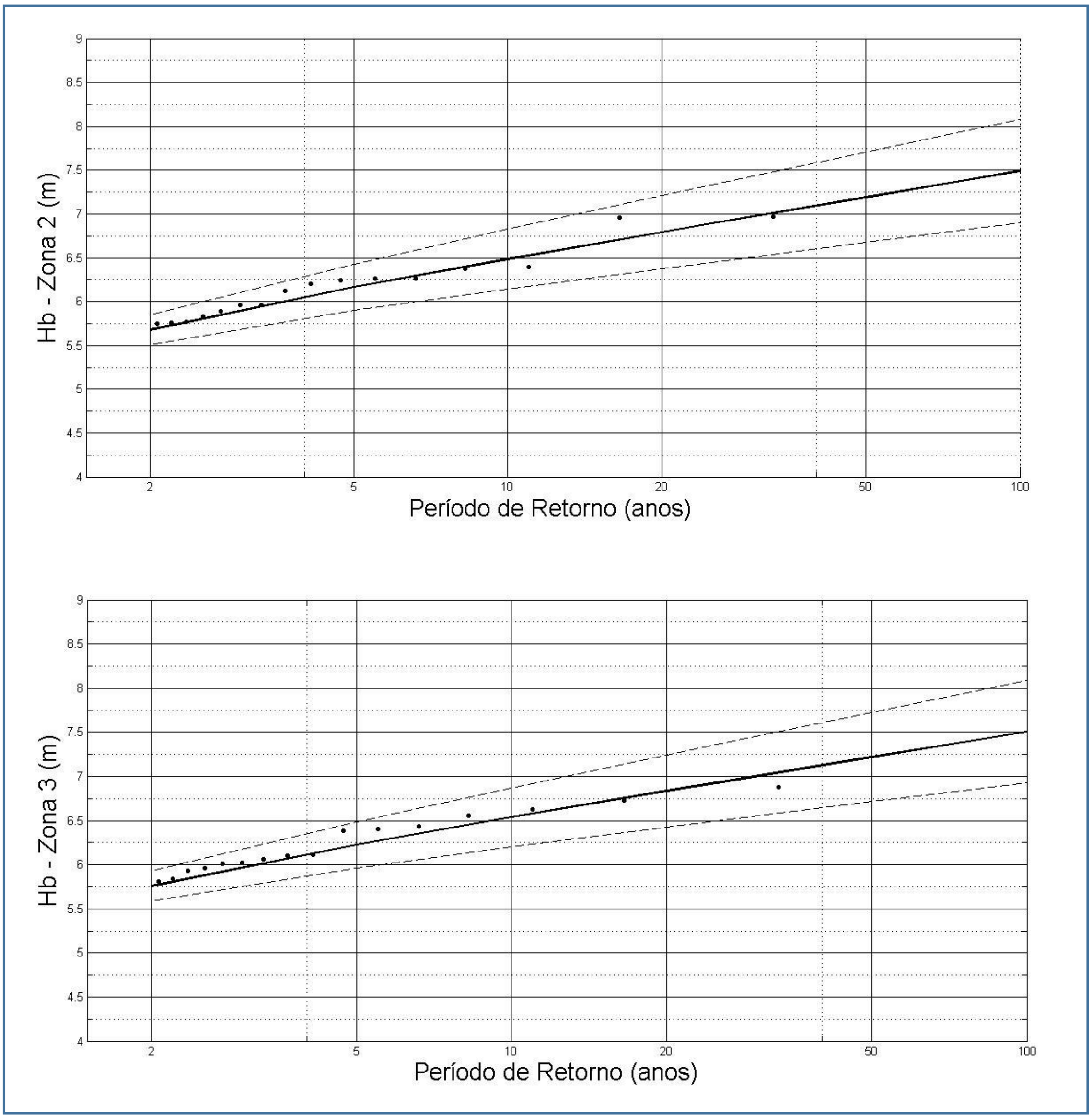


Tabela B2. Resultado do cálculo por período de retorno de profundidade de quebra (hb), tempo-resposta do perfil praial (Ts) e retração por tempestade (Rt)

Praia	Setor N_S	hb10	hb50	Ts10	Ts50	Rt10	Rt50
Tijucas	1,00	6,80	7,60	3,19	3,34	4,87	181,20
Tijucas	2,00	6,20	6,90	15,63	16,94	1,23	92,65
Tijucas	3,00	6,20	6,80	1,32	1,41	3,09	91,08
Praia de Fora	4,00	7,40	8,10	43,16	46,71	0,32	31,00
Palmas	5,00	7,40	8,10	40,93	44,29	0,53	50,61
Palmas	6,00	7,30	8,10	38,78	41,50	0,72	67,52
Palmas	7,00	7,30	8,00	75,74	82,76	0,25	26,33
Praia Grande	8,00	7,30	8,00	35,78	38,70	0,55	51,80
Bananeiras	9,00	7,30	8,10	37,82	40,48	0,37	35,53
Praia das Cordas	10,00	7,20	8,00	30,86	32,99	0,71	65,91
Cordas	11,00	7,00	7,80	50,00	54,03	0,33	33,21
Praia Brava	12,00	7,20	7,90	56,83	62,03	0,42	41,60
Praia Brava	13,00	7,40	8,20	44,48	47,64	0,51	50,00
Praia Brava	14,00	7,40	8,20	44,48	47,64	0,51	50,00
Ingleses	15,00	7,20	8,00	67,33	72,85	0,35	37,68
Ingleses	16,00	7,50	8,30	11,61	12,28	2,37	158,28
Ingleses	17,00	7,50	8,30	10,58	11,19	3,21	206,84
Santinho	18,00	7,30	8,10	102,03	111,28	0,17	19,24
Santinho	19,00	7,40	8,20	79,72	86,34	0,17	18,28
Mocambique	20,00	6,90	7,60	41,56	45,57	0,55	54,86
Mocambique	21,00	7,10	7,80	57,07	62,65	0,39	39,73
Mocambique	22,00	7,30	8,00	54,91	59,95	0,32	30,99
Mocambique	23,00	7,20	7,90	46,93	51,20	0,45	44,82
Barra da Lagoa	24,00	7,70	8,40	13,19	14,14	1,11	76,52
Barra da Lagoa	25,00	7,70	8,40	14,07	15,09	1,29	89,53
Praia da Galheta	26,00	7,30	8,00	93,94	103,28	0,12	13,76
Praia da Galheta	27,00	7,40	8,20	7,77	8,21	2,91	161,64

Mole	28,00	6,70	7,40	21,18	23,03	0,59	49,39
Mole	29,00	6,90	7,60	27,21	29,62	0,77	70,26
Joaquina	30,00	7,60	8,30	10,48	11,22	2,03	121,74
Joaquina	31,00	6,50	7,20	15,23	16,53	0,65	48,58
Joaquina	32,00	6,50	7,20	15,23	16,53	1,17	87,60
Campeche	33,00	6,70	7,40	23,91	26,00	0,63	53,97
Campeche	34,00	7,30	8,10	6,65	7,02	2,39	126,33
Morro das Pedras	35,00	6,60	7,30	44,39	48,85	0,36	35,42
Morro das Pedras	36,00	7,20	7,90	113,79	125,65	0,23	25,49
Morro das Pedras	37,00	7,20	7,90	50,20	54,79	0,40	40,48
Armacao	38,00	6,10	6,70	4,84	5,23	2,09	95,46
Armacao	39,00	6,30	6,90	1,17	1,25	3,46	98,41
Armacao	40,00	7,70	8,40	14,98	16,06	2,47	178,91
Armacao	41,00	7,70	8,40	14,98	16,06	1,98	146,58
Matadeiro	42,00	7,70	8,40	14,79	15,86	1,40	103,10
Matadeiro	43,00	7,50	8,30	56,67	60,75	0,35	37,08
Lagoinha do Leste	44,00	7,50	8,20	8,69	9,30	2,86	165,80
Lagoinha do Leste	45,00	6,80	7,50	50,43	55,54	0,46	47,15
Pantano do Sul	46,00	7,60	8,30	13,48	14,45	0,96	67,83
Pantano do Sul	47,00	6,90	7,50	74,14	82,39	0,12	12,76
Solidao	48,00	7,20	7,90	66,15	72,24	0,17	19,19
Solidao	49,00	7,50	8,20	10,89	11,66	1,16	77,79
Naufragados	50,00	7,50	8,20	11,72	12,54	1,13	78,55
Naufragados	51,00	7,10	7,80	68,35	74,65	0,17	18,18
Pinheira	52,00	7,70	8,40	14,20	15,22	0,96	68,60
Pinheira	53,00	7,50	8,30	101,86	110,40	0,13	14,32
Prainha da Guarda	54,00	7,00	7,70	61,45	67,46	0,32	33,36

APÊNDICE C – ZONA TAMPÃO CONSIDERADA NA ANÁLISE DE IMPACTO DE EROSÃO

A extensão do impacto de erosão foi delineada considerando-se uma zona tampão de 50 m a partir do recuo máximo da linha de costa calculada em cada setor e cada cenário (Figura C1 e C2).

Figura C1. Extensão do impacto de erosão para o período de retorno de 10 anos (T10)

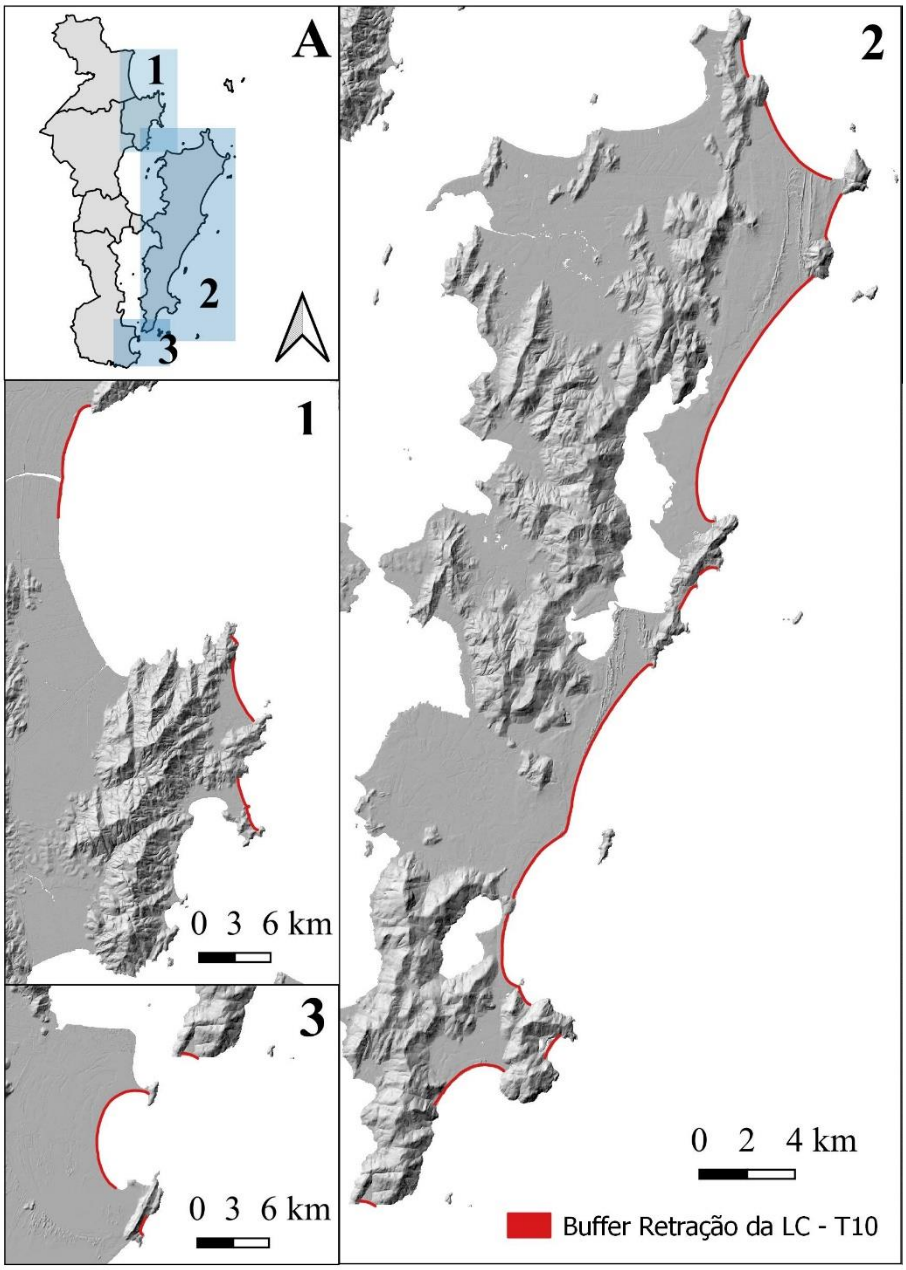
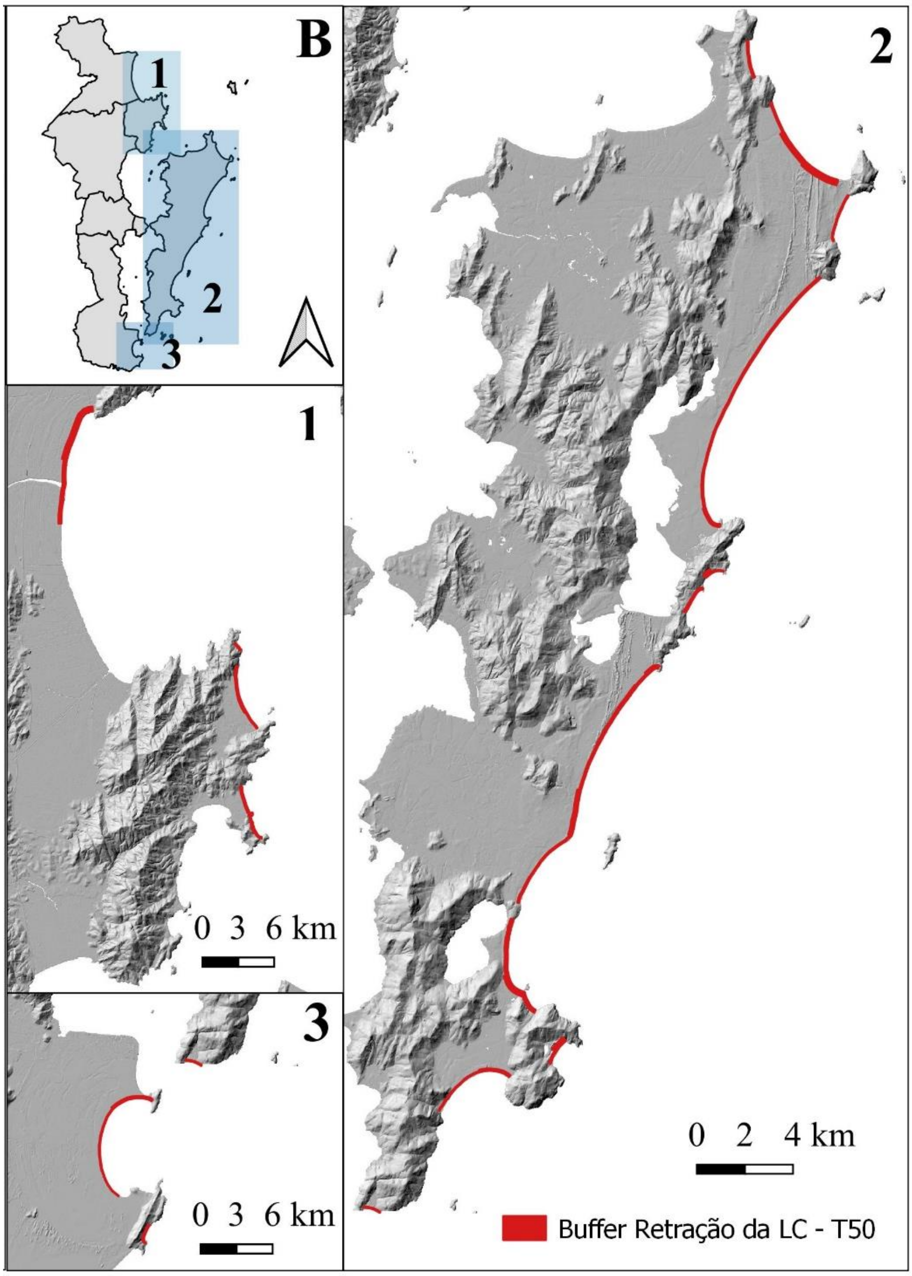


Figura C1. Extensão do impacto de erosão para o período de retorno de 50 anos (T50)



APÊNDICE D – INDICADOR DE VULNERABILIDADE SOCIAL: DADOS COMPLEMENTARES

1. Detalhamento dos procedimentos metodológicos

Após a seleção dos parâmetros para a construção do Índice de Vulnerabilidade Social foi realizado o reescalonamento das variáveis para os cenários T10 e T50 através da equação a seguir:

$$V = \frac{X - min}{máx - min}$$

Onde V é o valor reescalonado e X é o valor original da variável. Esta equação foi aplicada com inversão de mínimos e máximos para as variáveis inversamente proporcionais à vulnerabilidade (renda e responsáveis alfabetizados). Posteriormente os dados foram especializados de acordo com a malha de setores do IBGE e as variáveis foram integradas através da fórmula adaptada de Tapsell et al. (2002), resultando em um índice de vulnerabilidade social para cada setor censitário (Figura D1).

A fim de aprimorar o indicador, os setores censitários foram reduzidos de acordo com a intersecção dos polígonos de uso do solo classificados como área urbanizada. Os dados foram então analisados de acordo com a extensão de impacto mapeada como descrito no item 4.2.1.

Figura D1. Índice de Vulnerabilidade Social (IVS) calculado à nível de setor censitário