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VARIABILIDADE ESPAÇO-TEMPORAL DOS DESLOCAMENTOS DA LINHA DE COSTA NO RIO GRANDE DO SUL

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RESUMO

Este estudo apresenta uma análise regional das condições atuais em que se encontra a costa do Rio Grande do Sul com base em parâmetros como: ocupação urbana, crescimento populacional, nível de alteração antrópica das praias, variabilidade temporal e espacial das flutuações da linha de costa de curto termo (sazonal e interanual), evolução costeira de longo termo (Holoceno) e classes de gerenciamento costeiro. As alterações antrópicas ao longo da praia (incluindo o nível de urbanização) foram observadas em levantamentos de campo realizados em 2000. Dados de crescimento populacional foram obtidos dos Censos Populacionais de 1991 e 2000 realizados pelo IBGE. As variações da linha de costa foram determinadas através da comparação entre as posições da linha de costa mapeadas entre 1997 e 2002 pelo método de DGPS cinemático. As causas das variações temporais e espaciais da linha de costa foram avaliadas em relação ao tamanho de grão, tempestades, ENSO, orientação da linha de costa e transporte longitudinal. Atualmente, 20% do litoral gaúcho encontra-se urbanizado, enquanto um terço de sua extensão apresenta algum nível de alteração antrópica. As análises de variações da linha de costa mostraram diferenças regionais na magnitude dos deslocamentos, no padrão sazonal das variações e no intervalo de tempo em que a linha de costa retorna a sua configuração e posição antecedentes. No litoral sul, os deslocamentos anuais da linha de costa mostram acresção dominando ao norte do Albardão e alternância entre acresção e erosão ao sul. No litoral médio, as flutuações anuais da linha de costa apresentam um padrão rítmico, no qual áreas em erosão ocorrem adjacentes a áreas em acresção em um ano e apresentam movimentos opostos no ano seguinte. Os deslocamentos anuais no litoral norte também apresentam um comportamento rítmico e antagônico, em que a acresção praial dominante em um ano é seguida pela erosão em outro. O comportamento antagônico dos deslocamentos anuais da linha de costa coincide com os eventos de ENSO. Foi observado também que a linha de costa tende a retornar a sua forma e posição anteriores, sazonalmente no litoral sul, anualmente no litoral médio e a cada 19 meses no litoral norte. A variabilidade espacial na resposta da linha de costa às mudanças sazonais e interanuais deve-se a uma combinação de fatores, incluindo granulometria, orientação da linha de costa e transporte sedimentar ao longo da costa. A análise regional da costa do RS permitiu classificá-la em quatro classes de manejo: (1) *áreas de manejo crítico*, ocorrem em 177 km ou 29% da costa do RS e consistem basicamente nas áreas urbanizadas, concentradas principalmente no litoral norte, (2) *áreas prioritárias*, ocorrem em 198 km ao longo do litoral médio, ocupando 32% da costa do RS, (3) *áreas latentes* ocorrem em 65 km ou 10% da costa, localizados no litoral sul entre o Hermenegildo e o Albardão e (4) *áreas naturais*, ao longo de 178 km ou 29% da costa gaúcha, encontradas no litoral central e sul.

ABSTRACT

This study presents a regional analysis of the Rio Grande do Sul shoreline based on: intensity of beachfront urban development, population growth, human impacts in the beach system, temporal and spatial variability of the short-term shoreline changes (seasonal and interannual), long-term coastal evolution (Holocene), and classes of coastal management. Human impacts (including the intensity of beachfront development) were observed in field surveys conducted in 2000. Data on population growth were obtained from the 1991 and 2000 Census provided by IBGE. The shoreline was mapped five times from 1997 to 2002 using the kinematic DGPS method and shoreline changes were determined by comparing displacements in shoreline positions. The influence of grain size variations, storms, ENSO, shoreline orientation, and longshore sediment transport in determining the alongshore and temporal variability of shoreline changes was analyzed. About 20% of the Rio Grande do Sul coastline is developed, and nearly one third of its length shows some level of human impacts. The analysis of the shoreline changes showed regional differences in the magnitude of displacements, in their seasonal effects, and in the time-interval in which the shoreline returns to a previous shape and position. Along the southern sector, annual shoreline changes show accretion dominating north of Albardão and alternating areas of erosion and accretion to the south. Along the central sector, annual changes show a rhythmic pattern with alternating areas of erosion and accretion showing opposite trends in the following year. Annual shoreline changes along the northern sector show similar rhythmic and opposite patterns, although erosion dominates in one year and is followed by erosion in the next. The opposite behavior of the annual shoreline movements is coincident with ENSO events. It was observed also that the shoreline tends to return to a previous shape and position, seasonally along the southern sector, annually along the central sector, and after 19 months in the northern sector. The alongshore variability in the response of the shoreline to the seasonal and interannual effects is due to a combination of factors including grain size, shoreline orientation, and longshore sediment transport. The regional analysis of the Rio Grande do Sul coast allowed to define four classes of management: (1) *critical areas*, occur along 177 km or 29% of the coastline length and comprises mainly the urbanized areas located mainly along the northern sector, (2) *priority areas*, occur along 198 km of the central sector and occupy 32% of the states coast, (3) *areas of future concern* occur along 65 km or 10% of the coast, located along the southern sector, between Hermenegildo and Albardão, and (4) *natural areas*, along 178 km or 29% of the coastal length, present along the southern and central sectors.

CAPÍTULO 1

INTRODUÇÃO

INTRODUÇÃO

O crescimento demográfico acelerado nas cidades litorâneas e o aumento progressivo da urbanização costeira são fenômenos observados no Brasil e no mundo. O turismo, a recreação, o comércio e outras atividades relacionadas às praias e a outros ambientes costeiros têm sido o suporte econômico de um número crescente de comunidades. A dependência econômica local e regional de atividades ligadas ao uso e exploração da zona costeira tem resultado num constante conflito do uso do solo, geralmente incompatível com as preocupações preservacionistas atuais. Assim, a demanda acelerada pelos recursos naturais costeiros torna imprescindível a compreensão dos processos dinâmicos ali atuantes em diversas escalas de tempo e espaço. Conhecer as mudanças da linha de costa no presente e no passado, bem como fazer projeções para o futuro, é essencial para a maioria dos projetos de engenharia e planejamento na zona costeira (Galgano & Leatherman, 1991; Morton, 1997; Douglas *et al*., 1998; Honeycutt *et al*., 2001; Pajak & Leatherman, 2002). Entre as aplicações práticas dos estudos das oscilações da linha de costa estão: a identificação de áreas de risco, a quantificação da perda de terrenos, a determinação de linhas de recuo para construções costeiras e a delimitação de zonas suscetíveis à inundação (NRC, 1990).

Embora as variações da linha de costa sejam processos tridimensionais (Parson *et al*., 1999), a posição e o deslocamento horizontal da linha de costa são as variáveis que comumente servem como indicadores de erosão e acresção (Morton *et al*., 1993; Stockdon *et al*., 2002). A rapidez com que as alterações nos sistemas costeiros estão acontecendo torna necessária a obtenção de dados precisos, em grandes áreas, de forma rápida e que permita atualização constante. Recentemente, o enfoque principal dos estudos costeiros tem sido as variações de larga escala (quilômetros de extensão na ordem de anos) na batimetria adjacente à costa e na topografia da praia; pois é nesta escala que as decisões de gerenciamento são tomadas e que uma melhor compreensão científica é necessária (Stockdon *et al*., 2002). Enquanto mapas topográficos e fotografias aéreas têm sido as fontes mais comuns de dados de longo-termo e larga escala da posição da linha de costa (*e.g*. Dolan *et al*., 1980; Smith & Zarillo, 1990; Galgano & Leatherman, 1991; Hapke & Richmond, 1999), a aplicação de tecnologias avançadas, como o DGPS (*Differencial Global Positioning System*) cinemático e os sistemas lidar (*Light Detection and Ranging*), tem agilizado a obtenção de dados precisos em áreas extensas (*e.g*. Brock *et al*., 1999, 2002; Parson *et al*., 1999; Stockdon *et al*., 2002).

Na Europa e nos EUA, é crescente a implementação de planos de manejo costeiro regionais subsidiados por órgãos públicos, tanto a nível estadual (como ocorre nos estados americanos da Flórida, Nova Jersey, Califórnia, entre outros) quanto nacional (como na Holanda). Embora os programas de monitoramento costeiro no Brasil estejam muito aquém de países como os EUA, Austrália, Holanda e Espanha, observa-se que nos últimos anos o assunto vem despertando interesse de órgãos governamentais e instituições de pesquisa. Contribuiu para isto o Plano Nacional de Gerenciamento Costeiro (PNGC), criado em 1988 (Lei 7.661, de 16/05/1988) e detalhado em 1990 pela Resolução No. 01/90 da Comissão Interministerial para Recursos do Mar (http://www.mma.gov.br/port/sqa/projeto/gerco/planocac.html). O resultado é o crescente número de projetos de pesquisa integrada a nível nacional, regional e internacional, como os projetos *Orla* (financiado pela Secretaria de Patrimônio da União, Ministério do Planejamento) e *Atlas de Erosão Costeira*, à nível nacional, e o projeto *Erosão Costeira: Causas, Análise de Risco e sua Relação com a Gênese de Depósitos Minerais* (financiado pela Organização dos Estados Americanos), abrangendo a costa do Rio Grande do Sul, Uruguai e Argentina (Martins *et al*., 2002). O PNGC estabelece as diretrizes básicas para os Programas de Gerenciamento Costeiro estaduais (GERCO), que no Rio Grande do Sul (RS) é coordenado pela Fundação Estadual de Proteção Ambiental Henrique Luis Roessler (FEPAM). Com base na maior ocupação urbana, a FEPAM estabeleceu prioridade para implantação do Zoneamento Ecológico-Econômico e o Enquadramento dos Recursos Hídricos no litoral norte (FEPAM, 2000), enquanto os litorais médio e sul, ainda pouco ocupados, esperam regulamentação.

Planos de gerenciamento costeiro integrado visam promover o desenvolvimento sustentável buscando proteger os recursos naturais, buscando um equilíbrio entre as atividades antrópicas (sócio-econômicas e culturais) e o ambiente físico (Cicin-Sain & Knecht, 1998). Desta forma, a implementação de estratégias de manejo costeiro requer um certo grau de conhecimento dos processos dinâmicos atuantes ao longo da costa. O conhecimento das relações entre os processos costeiros e sua influência nas variações morfológicas ao longo da costa do Rio Grande do Sul vem aumentando nos últimos anos, mas muitas lacunas ainda precisam ser preenchidas. Este estudo apresenta uma abordagem regional de fatores inerentes à pressão antrópica e à dinâmica de processos naturais utilizados para definir setores da costa que apresentam diferentes necessidades de manejo. Para tanto, a costa gaúcha foi caracterizada em função do estado atual de alteração das praias, nível de ocupação urbana, taxas de crescimento populacional, variações da linha de costa de curto termo e evolução geológica de longo termo. Atenção especial foi dada à identificação de padrões regionais no comportamento das variações na posição da linha de costa em escalas de tempo sazonal e interanual e sua variabilidade ao longo da costa. Adicionalmente, discute-se os fatores que influenciam a variabilidade espacial e temporal das flutuações na posição da linha de costa, como granulometria dos sedimentos praias, orientação da linha de costa, transporte litorâneo, tempestades, El Niño-Southern Oscillation (ENSO) e transporte longitudinal. Desta forma, este estudo contribui para ampliar a compreensão da variabilidade dinâmica da linha de costa e suas inter-relações, apresentando resultados inéditos para o RS no que se refere à extensão e a continuidade da área de estudo e os métodos adotados.

OBJETIVOS

O objetivo geral deste estudo consiste em determinar padrões de comportamento das variações da linha de costa e avaliar o estado de alteração antrópica das praias para identificar áreas críticas e prioritárias para o gerenciamento costeiro no RS. Para atingir este objetivo geral, as seguintes etapas de trabalho foram executadas:

(a) Classificar a costa do RS em função do atual estado de alteração antrópica de suas praias, incluindo ocupação urbana, estado de preservação do sistema praia-duna, taxas de crescimento populacional e impactos antrópicos dominantes.

(b) Montar um banco de dados com as posições da linha de costa obtidas através de mapeamentos realizados por DGPS cinemático entre 1997 e 2002 e determinar padrões de comportamento ao longo do tempo e ao longo da costa.

(c) Classificar a costa gaúcha em função do comportamento das variações da linha de costa, determinando áreas com tendências à erosão, estabilidade ou acresção.

(d) Avaliar os fatores causadores da variabilidade espacial e temporal observada nos padrões de comportamento da linha de costa.

(e) Correlacionar as características ambientais regionais, a intensidade de uso e ocupação, a evolução costeira de longo-termo e as variações da linha de costa de curto-termo para identificar diferentes classes de gerenciamento costeiro.

JUSTIFICATIVAS

As análises das variações na posição da linha de costa cujos dados foram obtidos pelo método de DGPS cinemático ao longo de aproximadamente 610 km da costa do RS constituem um estudo inédito no Brasil no que se refere à extensão da área de estudo, ao detalhamento espacial apresentado e ao método utilizado. Observando trabalhos similares publicados na literatura internacional, nota-se que a extensão da área de estudo torna este trabalho sem precedentes também à nível mundial, já que as maiores extensões costeiras contíguas mapeadas por DGPS são de 130 km ao longo da costa da Carolina do Norte, EUA (List & Farris, 1999; List *et al.*, 2003). A continuidade e a rapidez na obtenção de dados por DGPS cinemático possibilitam avaliar como diferentes trechos da costa respondem a condições energéticas semelhantes. Esta continuidade ao longo da costa amplia o conhecimento que se tem hoje das variações costeiras no RS, que é basicamente pontual, limitado a poucos locais e esparso ao longo da costa.

A identificação da relação entre causa e efeito para explicar a variabilidade temporal e espacial do comportamento das mudanças da linha de costa, a identificação das áreas suscetívies à erosão e a quantificação das magnitudes das flutuações da linha de costa são resultados deste estudo que contribuem para aprimorar a compreensão da dinâmica costeira no RS. Além disso, a análise integrada em escala regional das variações da linha de costa em diferentes escalas de tempo associadas às tendências de crescimento populacional fornece subsídios importantes para definir estratégias adequadas de gerenciamento costeiro.

ORGANIZAÇÃO DA TESE

Esta tese foi elaborada na forma de apresentação de artigos que correspondem às diferentes etapas de trabalho realizadas neste estudo. O primeiro capítulo é introdutório, apresentando os objetivos, as justificativas e a organização da tese, e os métodos utilizados no seu desenvolvimento. Os capítulos 2, 3, 4, 5 e 6 contêm os artigos publicados ou submetidos à revistas científicas e apresentam os principais resultados obtidos. Desta forma, inevitavelmente occorrem repetições de texto nesses capítulos visto que os artigos versam sobre a mesma área de estudo e estão incorporados nesta tese exatamente como foram enviados às revistas. As únicas modificações feitas nos artigos referem-se à numeração das figuras, que se distinguem pela introdução do número do capítulo ao qual pertencem.

O artigo apresentado no Capítulo 2 é entitulado "*Coastal development and human impacts along the Rio Grande do Sul beaches*" e foi publicado em 2003 no *Journal of Coastal Research*. Este capítulo classifica setores da costa do RS com base nas suas características ambientais dominantes e no estado de alteração das praias decorrente de interferências antrópicas. O Capítulo 3 apresenta o artigo "*Long- and short-term coastal erosion in southern Brazil*" publicado em 2002 no *Journal of Coastal Research*. Este capítulo faz uma análise crítica sobre os trabalhos que abordam a erosão costeira no RS e discute as discrepâncias e semelhanças entre os resultados apresentados em diferentes estudos. No Capítulo 4, o artigo "*Alongshore patterns of shoreline movements in southern Brazil*", aceito para publicação no *Journal of Coastal Research*, descreve as diferenças regionais nos padrões de variação da linha de costa de curto-termo entre os três grandes setores costeiros do RS (litoral sul, médio e norte). Este capítulo também apresenta uma comparação entre as variações de curto-termo da linha de costa no litoral norte com a evolução costeira de médio e longo prazos. O Capítulo 5 apresenta o artigo "*Seasonal and interannual influences on the patterns of shoreline changes in Rio Grande do Sul, southern Brazil*", submetido para publicação no *Journal of Coastal Research*. Neste capítulo, o comportamento das variações da linha de costa de curto-termo observados no litoral sul, médio e norte é detalhado e a influência de fatores como: a granulometria dos sedimentos praias, a orientação da linha de costa, as tempestades, ENSO e o transporte por deriva litorânea, na sua variabilidade espacial e temporal é analisada. O artigo apresentado no Capítulo 6 intitula-se

"*Shoreline changes and coastal evolution as parameters to identify priority areas for management in Rio Grande do Sul*" e foi submetido para publicação na revista Pesquisas em Geociências. Este capítulo faz uma análise regional da costa do RS em função de fatores abordados nos capítulos anteriores, como o nível de urbanização e alteração das praias, variações da linha de costa de curto período e evolução costeira no Holoceno. Através da análise integrada desses fatores, quatro classes de gerenciamento costeiro são identificadas para a costa do RS: áreas de gerenciamento crítico, áreas prioritárias, áreas latentes e áreas naturais. O capítulo 7 apresenta as conclusões finais da tese integrando o que foi apresentado em cada artigo e, finalmente, no Capítulo 8, estão listadas as referências citadas nos capítulos anteriores.

MÉTODOS

A costa do RS foi classificada em função das características ambientais dominantes e o seu estado de alteração decorrente de interferências antrópicas com base em observações de campo obtidas em maio e julho de 2000. O método consistiu em conduzir um veículo com tração nas quatro rodas pela praia anotando as características observadas e marcando a distância ao longo da costa pelo odômetro do veículo. Nas excursões de campo, 556 km dos 618 km da costa do estado foram mapeados, observando-se as seguintes características:

(a) **Urbanização**. Foram determinados três níveis de urbanização em função da porcentagem da extensão da beira-mar que se encontrava urbanizada: intensa (ocupação em mais de 70% da linha de costa), moderada (ocupação da beira-mar entre 30 e 70%) e baixa ou não ocupada (ocupação menor do que 30%). Anotou-se também os tipos de construções (*e.g.*, prédios, casas, residenciais, comerciais), o padrão de construção médio em cada setor (alto, médio e baixo) e o local onde a primeira faixa de construções está assentada (no pós-praia, nas dunas ou atrás das dunas).

(b) **Alterações antrópicas**. Todo tipo de interferência decorrente de atividades humanas foi registrado, incluindo: lixo sobre a praia, retirada de areia da praia e dunas, presença de obras de proteção costeira (*e.g.*, muros de contenção, enrocamentos, fixação ou reconstrução de dunas), reflorestamentos comerciais, tráfego sobre a praia, plataformas de pesca, entre outras. Considerou-se alterados, os trechos onde as atividades antrópicas causaram mudanças percebidas visualmente nas características naturais da praia.

Desde 1997, a linha de costa no RS vem sendo monitorada por pesquisadores do Centro de Estudos de Geologia Costeira e Oceânica (CECO) e do Instituto de Pesquisas Hidráulicas (IPH) da UFRGS utilizando o método de DGPS cinemático (Morton *et al.*, 1993; Morton, 1997; Toldo *et al.*, 1999). Os 618 km da costa gaúcha foram percorridos com o DGPS instalado em um veículo que se desloca com velocidade de 50 km/h obtendo as posições da linha de costa em intervalos de tempo regulares. Em 1997, dois Garmin GPS 100 Personal Surveyor foram utilizados, um deles instalado em um veículo em movimento registrando posições a cada 5 s e o outro, operando no modo estático, foi posicionado em locais previamente escolhidos com o objetivo de aumentar a precisão das leituras para 3 m. Nos anos seguintes, a correção dos dados foi feita pela antena de Porto Alegre, e não mais pelo GPS em modo estático. A partir de 2000, passou-se a utilizar o equipamento Trimble GPS 4600, com precisão de 1 m no modo de navegação, registrando as leituras a cada 3 s. A feição indicadora da linha de costa mapeada em 26-28/11/1997, 17-19/11/1998, 10-11 e 19/11/1999 e 26-28/06/2000 foi a linha d'água (*swash line*). O indicador mapeado em 15-17/04/2002 foi a linha deixada pela última maré alta ou a *high water line* (HWL), que é o indicador mais utilizado por ser facilmente identificado como sendo o limite entre areia seca e areia úmida (Pajak & Leatherman, 2002; Morton, 1997; Crowell *et al*., 1991; Dolan *et al*., 1980). Para efeito de comparação com as outras linhas, a posição da linha de 2002 foi corrigida conforme descrito no Capítulo 5. Importante ressaltar que estas feições foram escolhidas como indicadoras da linha de costa por serem as únicas contínuas ao longo de toda a área de estudo, além de serem as únicas que permitem mapeamento utilizando-se o DGPS instalado em um veículo.

A visualização das linhas mapeadas e as medições das distâncias entre elas foram realizadas através do programa ArcView GIS 3.2. Inicialmente, as medições foram feitas manualmente, adotando-se um procedimento que pode ser descrito em três etapas:

(1) **Criação de "marcos virtuais"**. Foi gerado um arquivo de pontos no ArcView, onde cada ponto representa um “marco virtual” ao longo da costa. Esses marcos servem como ponto de referência para as medições das distâncias entre as diferentes linhas de mapeamento. Os marcos foram gerados sobre a linha de costa mapeada em 2000, com intervalos de aproximadamente 500 m entre eles. Os marcos são numerados sequencialmente a partir do extremo sul, ou seja, o marco de número 1 localiza-se próximo da barra do Chuí (Figuras 2.1 e 2.2). Uma lista com todos os 1121 marcos gerados e suas respectivas coordenadas (em sistema UTM), obtidas em escala de 1:50 na tela de trabalho do ArcView, foi organizada em planilha eletrônica (MS Excel 2000), que serviu de base para o banco de dados das variações da linha de costa.

(2) **Definição das *transects***. As *transects* são linhas definidas perpendicularmente à linha de costa de 2000 a partir dos marcos virtuais, sobre as quais foram feitas as medições das distâncias entre as demais linhas de costa mapeadas. As *transects* foram definidas em intervalos de 1 km, ou seja sobre marcos virtuais alternados. Ao todo foram criadas 568 *transects* numeradas de acordo com os marcos aos quais estão ligadas, organizadas em um arquivo de linhas no ArcView.

(3) **Medições das distâncias entre as linhas de mapeamento**. As medições de distâncias entre as linhas de mapeamento foram realizadas sobre as *transects* (*i.e.*, em intervalos de 1 km ao longo da costa), em escalas entre 1:20 e 1:150 na tela de trabalho do ArcView. Os valores registrados na planilha eletrônica representam o deslocamento de uma linha em relação às outras e receberam valores negativos quando o deslocamento foi em direção à costa (erosão da linha de costa) ou positivos, quando o deslocamento foi em direção ao mar (acresção).

No Capítulo 3, as tendências de variação da linha de costa apresentadas no texto foram baseadas na comparação da linha de costa obtida em 2000 através do DGPS cinemático com a linha de costa digitalizada a partir de cartas topográficas do exército brasileiro (escala de 1:50.000) datadas de 1975. Os deslocamentos da linha de costa entre as duas linhas foram medidos manualmente através do programa ArcView 3.2, conforme o procedimento descrito acima. Nos capítulos posteriores, o programa *Digital Shoreline Analysis System 2.0* (DSAS) desenvolvido pelo *U.S. Geological Survey* (Thieler *et al.*, 2003) especificamente para calcular taxas de variação da linha de costa foi utilizado para verificar as medidas de variação da linha de costa obtidas manualmente para o período entre novembro/1997 e abril/2002. O comportamento das variações da linha de costa observado pelos dois métodos foi semelhante, embora os valores nominais das estatísticas obtidas tenham apresentado uma pequena diferença. Esta diferença deve-se à grande variabilidade longitudinal na posição da linha de costa e ao fato de que o DSAS permitiu aumentar a densidade espacial dos dados, que foram estimados em intervalos de 250 m, enquanto os dados obtidos manualmente foram obtidos em intervalos de 1000 m. Os capítulos 4, 5 e 6 apresentam dados de variação da linha de costa obtidos através do DSAS.

Tanto os dados obtidos pelas medições manuais (identificação dos marcos virtuais, suas coordenadas geográficas, as distâncias medidas entre as linhas de costa e as escalas de medição) quanto os obtidos pelo DSAS foram organizados em planilha eletrônica, a partir da qual foram gerados gráficos de deslocamento da linha de costa e calculados os parâmetros estatísticos das linhas de deslocamento. Nos gráficos, os deslocamentos em direção ao mar (acresção) são representados por valores positivos e os deslocamentos em direção à costa por valores negativos (erosão). A análise desses gráficos permitiu identificar padrões de variação da linha de costa para os três setores do litoral e seus efeitos sazonais e interanuais, descritos nos Capítulos 4 e 5. Os gráficos de taxas de variação da linha de costa foram utilizados para determinar as tendências de curto-termo e comparar com a evolução costeira de médio e longo prazos (Capítulos 4 e 6).

Adicionalmente, taxas de variação da linha de costa foram estimadas a partir de fotografias aéreas verticais datadas de janeiro de 1974 e fevereiro de 1989 (escala de 1:20.000) concedidas pelo Departamento Autônomo de Estradas de Rodagens (DAER), e fotografias aéreas digitais de pequeno formato datadas de 2000 obtidas pela Fundação Universidade Federal do Rio

Grande (FURG) utilizando o ADAR-1000 system (Fontoura & Hartmann, 2001). Pelo menos seis pontos de controle foram identificados em cada fotografia e as distâncias entre eles foram medidas para estabelecer erros decorrentes de distorções e da capacidade de identificar a localização exata dos pontos utilizados nas medições. A largura das praias foi medidas a cada 150 m ou 200 m em frente a pontos estáveis estabelecidos ao longo de pelo menos 2 km de extensão em cinco setores diferentes do litoral norte. Utilizando-se as medições obtidas em cada setor, taxas de variação médias foram estimadas para cada uma das praias. Os resultados dessas análises estão apresentados no Capítulo 4.

A identificação de áreas críticas e prioritárias para o gerenciamento costeiro no RS foi realizada correlacionando-se os fatores descritos nos Capítulos 2, 3, 4 e 5, ou seja, a intensidade de ocupação e uso, as variações da linha de costa de curto-termo e seus efeitos sazonais e temporais, a evolução costeira de longo-termo, além das taxas de crescimento populacional entre 1990 e 2000 fornecidas pelo Instituto Brasileiro de Geografia e Estatística (IBGE, 2000). Assim, foram definidas quatro classes que apresentam diferentes necessidades de manejo:

(1) **Áreas críticas**. São áreas que requerem medidas de gerenciamento costeiro corretivo. Apresentam urbanização intensa e/ou crescente ocupação e uso do solo, tendência à erosão e/ou destruição de estruturas costeiras durante eventos de alta energia, magnitudes de deslocamento da linha de costa que excedem a largura média da praia emersa, dunas primárias ausentes ou muito alteradas.

(2) **Áreas de ação prioritária**. São áreas sob pressão crescente em que urge a aplicação de medidas de gerenciamento preventivo. Apresentam urbanização moderada ou baixa, taxas de crescimento populacional acima da média do estado, recente intensificação do uso (turismo, valorização imobiliária, conflitos de interesses), tendência à estabilidade ou erosão no curto ou longo-termo e grandes magnitudes de deslocamento da linha de costa.

(3) **Áreas latentes**. São áreas que atualmente não se encontram sob grande pressão de uso, mas que num futuro próximo podem se tornar áreas de ação prioritária, portanto é aconselhável a implementação de medidas reguladoras de ocupação e uso. Apresentam sistema praia/duna preservado ou pouco alterado, urbanização moderada a baixa, e tendência à erosão ou estabilidade/acresção com grandes magnitudes de deslocamento da linha de costa. Em geral, ocorrem nas proximidades de áreas críticas ou prioritárias, ou são áreas não urbanizadas que recentemente tiveram vias de acesso ampliadas ou criadas.

(4) **Áreas naturais**. São as áreas que têm suas características naturais preservadas, não são urbanizadas, apresentam pouca pressão de uso e sem indícios de que essas condições serão alteradas em um futuro próximo. Podem apresentar tendência à erosão, estabilidade ou acresção.

CAPÍTULO 2

COASTAL DEVELOPMENT AND HUMAN IMPACTS ALONG THE RIO GRANDE DO SUL BEACHES, BRAZIL

Esteves, L.S.; Silva, A.R.P.; Arejano, T.B.; Pivel, M.A.G. & Vranjac, M.P. 2003. Coastal development and human impacts along the Rio Grande do Sul beaches, Brazil. *Journal of Coastal Research*, SI 35, 548-556.

ABSTRACT

Rio Grande do Sul (RS), the southernmost state in Brazil, has a 630-km long shoreline dominated by undeveloped sandy beaches. Unlike other states in Brazil, its colonization was more intense inland resulting in less than 5% of the state's population living in coastal cities. Many of the urbanized shores consist in small villages occupied only in the summer months. However, in the last decade there has been a change in this trend as coastal population is growing faster than the state's average. Many studies show that most of RS beaches are retreating, so it is urgent the implementation of a management plan to regulate occupation along the undeveloped shores to avoid new settlements in a hazardous coast. This work characterizes the RS coast based on the state of alteration of its beaches, which might be useful to support a statewide coastal management plan. The state shores were classified into four classes according to the dominant coastal environment (rocky headlands or open sandy beaches), type and distribution of developed shores (*i.e.* degree of urban development, type of beachfront constructions, urbanization in dune areas), and the impact of human activities. Developed and impacted shores comprise Classes 1, 2, and 3 that are prograding beaches influenced by headlands, accreted open sandy beaches, and mainly retreating open sandy beaches, respectively. Class 4 consists in undeveloped sandy beaches that represents 76% of the state shoreline length. Despite the long undeveloped shore segments, human activities are already impacting 31% of the RS shoreline. The length of impacted shores might increase in the near future (due to the implementation of new road access to undeveloped areas) as unplanned new development occurs along retreating shores.

Additional Index Words: Coastal environments, management, shore classification, beach erosion.

INTRODUCTION

Beach erosion is a worldwide problem (BIRD, 1985) that has been widely observed in the state of Rio Grande do Sul (RS), southern Brazil (Figure 2.1). According to TOLDO JR. *et al.* (1999), most of the RS coast is retreating at high rates, as along 378 km (about 60% of the total shore length) the shoreline retreated more than 100 m in 22 years. Several studies have addressed erosion in RS beaches indicating many natural and human-induced contributing factors to this process (*i.e.* SIEGLE, 1996; KLEIN and CALLIARI, 1997; TOMAZELLI *et al.* 1998; CALLIARI *et al.*, 1998; ESTEVES *et al.*, 1999; TOLDO JR. *et al.*, 1999). Shore erosion is still not a big issue in RS because, except for the northern sector, its shoreline is mainly undeveloped and coastal population is less than 5% of the state's total (9.7 million). Despite of the long undeveloped coastal segments and the small coastal population, the pressure of fast-growing, coastal urban centers is already impacting the shore.

Historically, colonization in the RS has been more intense inland than along the coast (MORAES, 1995). However, six of the ten cities that had the greatest population growth in the last decade are on the coast, evidencing that more people have moved from inland to live by the sea. Thus, it is evident that coastal population will grow faster in the near future and undeveloped areas soon will give place to new settlements. Considering that most of the state shores are retreating, it is urgent that a management plan based on local characteristics regulates new coastal development to avoid occupation of hazardous areas.

This work evaluates the present state of the RS beaches according to the characteristics and distribution of urban development and other human-induced alterations (*e.g.* sand mining, destruction of dunes, presence of shore protection structures). The goal is to present a comprehensive characterization of the state shorelines that provides valuable information to support a statewide coastal management plan. However, at this moment, characterization will be focused on the aspects of coastal development as many of the physical and morphological parameters that are very important to establish the best management practices will not be discussed in this paper due to space constrains.

STUDY AREA

The RS has a 630-km long coastline formed mainly by exposed fine sand beaches that have a NE-SW general orientation (Figure 2.1). These beaches are part of a large coastal plain extending from the headland of granite rocks at Cabo Polonio in Uruguay to the basalts of the Serra Geral Formation at Torres in the northern limit of the state (TOLDO JR. *et al.*, 1999). The coastal plain consists in a complex multiple sandy barrier composed of four lagoon-barrier depositional systems formed by sea-level fluctuations in the Quaternary (VILLWOCK, 1984). This coastal plain presents two large lagoons (Patos and Mirim) and several other small lagoons and lakes that trap sand from fluvial discharge, reducing the volume of sand reaching the shore (TOMAZELLI *et al.*, 1998). Two stabilized small inlets mark the northern and southern borders, the Mampituba river and the Chuí creek, respectively. The Tramandaí and the Patos Lagoon inlets are the only permanent discontinuities along the RS coast. They are both stabilized, but the second is much larger having two 4-km long jetties to fix the navigation channel of the Rio Grande Port, the third largest in Brazil. Innumerous permanent and temporary washouts cut the state beaches to discharge water accumulated behind the dunes and are important features to the sand balance.

Waves are the dominant hydrodynamic process along the RS coast, as the maximum tidal variation is less than 0.5 m (TOMAZELLI *et al.*, 1998). Winds from NE are dominant although southerly winds are the strongest and generate higher waves. As southerly waves have higher energy, the net longshore sediment transport is to the north, as can be observed in the accreted shores south of the Rio Grande jetty and the eroded profile of downdrift beaches. Storms associated to the passage of cold fronts frequently strike the coast in fall and winter months, mainly April and July (CALLIARI *et al.*, 1998). These events generally pile water onshore resulting in storm surges of about 1 m that combined to high-energy waves cause intense coastal erosion.

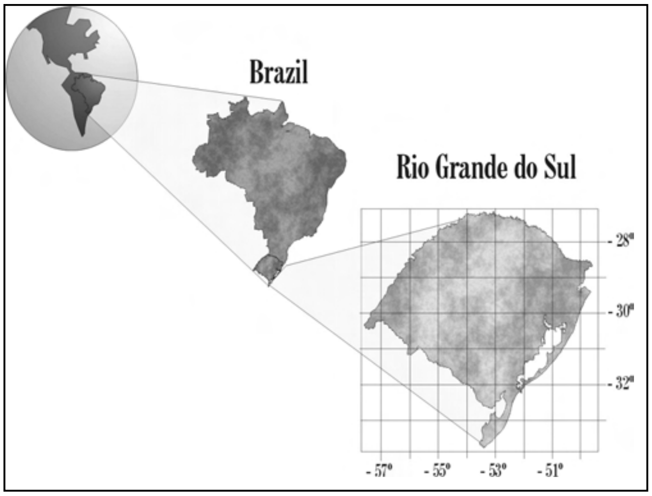

Figure 2.1. The study area consists in the 630-km long shoreline of Rio Grande do Sul, the southernmost state of Brazil.

Arbitrarily, the RS coast can be separated into three coastal sectors to facilitate description of its morphologic characteristics: (a) the northern sector extends from Torres (at the border with the state of Santa Catarina) to Dunas Altas (Palmares do Sul) in the south, (b) the central sector includes the beaches in between Dunas Altas and the Patos Lagoon inlet (São José do Norte), and (c) the southern sector consists in the shores from the Patos Lagoon inlet to the Chuí creek (at the border with Uruguay). The northern sector is a 136.5–km long highly urbanized shore that concentrates most of the coastal urban centers in the state (10 out of the 16 coastal towns). The central and southern sectors are mainly undeveloped, as the first presents only small fishing villages separated by long undeveloped shorelines and the second has only three urbanized beaches (Cassino, Hermenegildo, and Chuí).

Well-sorted fine quartzose sands dominate in the RS beaches, as it was observed in several studies that addressed specific beach segments such as from Arroio do Sal to Imbé

(WESCHENFELDER *et al.*, 1997) and Torres (PIVEL, 1997) in the northern sector, from Conceição Lighthouse to Hermenegildo (SIEGLE, 1996), in the southern and part of the central sector, and from Cassino to Chuí (CALLIARI and KLEIN, 1993) covering the southern sector. CALLIARI and KLEIN (1993) and SIEGLE (1996) observed slightly variations on beach sediments mean size in three areas: (1) south of the Conceição Lighthouse, mean sizes are coarser and less sorted due to the presence of shell fragments; (2) in Cassino, the influence of fine sediments from the Patos Lagoon causes a slightly decrease in the mean size, and (3) between Albardão Lighthouse and Hermenegildo there is a 30-km long segment (Concheiros do Albardão) that presents bimodal sediments composed by quartzose fine sands and bioclastic gravel.

CALLIARI and KLEIN (1993) classified beaches in the southern sector according to their morphodynamic state in three areas: from Cassino to Sarita Lighthouse beaches are dissipative; in the 30-km long Concheiros do Albardão, beaches are reflective to intermediate, and the remaining beaches are classified as intermediate. Beaches in the central coastal sector were classified as intermediate and highly susceptible to sand volume changes (BARLETTA *et al.*, 1999) while in the northern sector (Imbé and Tramandaí) beaches have been classified as intermediate to dissipative (TOLDO JR. *et al.*, 1993).

METHODS

This study characterizes the RS shorelines according to the dominant type of coastal environment and the present state of human-induced alterations. Most of the data was obtained in four field trips conducted in May and July 2000, which consisted in driving along the beaches taking notes on the characteristics of the backshore and dune fields and the type of urbanization that could be seen from the beach (mainly beachfront properties). The field trips covered about 556 km of the state 627-km long shoreline. Thus, 71 km of undeveloped shores were not mapped in this study (Figure 2.2) due to bad weather conditions experienced at the time. Although this shore segment was not covered at this time, it is well known from previous studies, and was included in the results to allow the entire shoreline length to be analyzed. Longshore distance was marked in the car odometer and registered in the field notes when coastal characteristics changed. Observations focused on beach and dune features, characteristics of urban development, and other human-induced alterations. Mapped features and classes are shown in Figure 2.2.

Presence of dunes, blowouts, and sand plains were registered. Dunes were classified as vegetated or non-vegetated and high (more than 1.5-m high) or low (less than 1.5-m high). The degree of urban development was established based on the percentage of beachfront lots that were built up and classified into three classes: (a) none or low development, when less than 30% of the area is occupied by buildings or other infrastructures; (b) moderate development, 30 to 70% of the shoreline is developed, and (c) highly developed shores, when more than 70% of the shoreline is built up. Additional notes consisted in the type (single or multi-family) and quality (high, normal, or low standards) of the major part of the buildings along a coastal sector, and where they were built (on the beach, dunes, or behind the dunes). Human-induced alterations visually observed in the beach system during the field trips were registered, including: sand mining, traffic, presence of debris, commercial afforestation, shore protection structures, dune fixation or reconstruction, fishing piers, and others. Shorelines were considered as altered where human activities visually changed and interfered in the natural coastal processes.

CLASSIFICATION OF COASTAL SEGMENTS

Many aspects of the RS coast have been extensively studied (*e.g.* beach morphodynamics, evidences of beach erosion) and many others still need to be evaluated (*e.g.* shoreline retreat rates, human impacts) to support management decisions. In an attempt to provide an overall picture of the state of RS beaches, a statewide evaluation of the human-induced impacts is presented (Figure 2.2). The RS shorelines can be grouped into four classes according to their natural characteristics and the impacts of human activities: (1) prograding beaches under the influence of rocky headlands, (2) impacted and prograding open sandy beaches, (3) developed and mainly eroding beaches, and (4) undeveloped open sandy beaches. Classes can be further subdivided in sectors presenting slightly differences in one or more criteria.

Class 1: Prograding Beaches under the Influence of Rocky Headlands

This class consists of the northernmost 8.4-km long shore segment (about 1.3% of the state shoreline length), comprising the beaches of Torres (Grande, Prainha, da Cal, Guarita, and Itapeva). The northern limit is the jetty of the Mampituba river that marks the border with the state of Santa Catarina and the southern limit is the small rocky promontory of Itapeva. Due to the littoral drift obstruction by the Mampituba jetty, Class 1 beaches have a positive sand balance that is easily observed in Praia Grande. There, beach widths have increased significantly in the last decade and artificial fixation of the dunes was conducted as they were invading the road and infrastructures located behind (PIVEL, 1997). Additionally, the presence of rocky headlands might contribute to the accreted condition of the other beaches, as even Prainha that often had its rocky basement completely exposed has shown a larger and thicker sand cover with time. These headlands are the only rocky shores in the state and consist of Botucatu sandstones accumulated in a desert environment and basalt (Serra Geral Formation) that flowed over them during the opening of the South Atlantic Ocean (upper Jurassic- lower Cretaceous) (VILLWOCK, 1984).

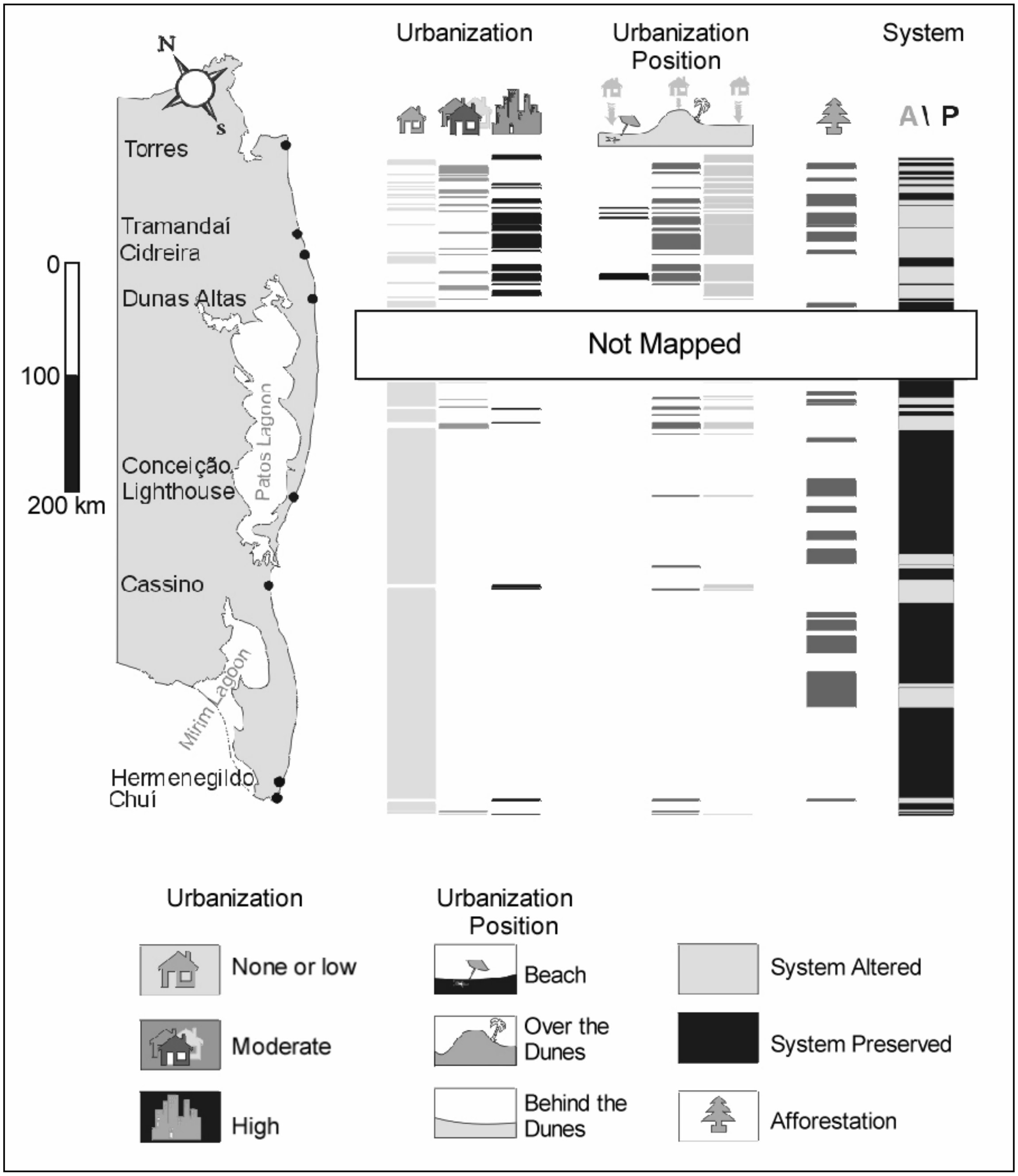

Figure 2.2. Classification of the RS coastline according to its state of human-induced alteration, degree and position of urban development, and presence of man-made forested areas. The northern sector (from Torres to Dunas Altas) consists mainly in highly developed and altered shores, while central (from Dunas Altas to the Patos Lagoon inlet) and southern sectors (south of the Patos Lagoon inlet) are mainly undeveloped and preserved beaches.

Torres is one of the largest coastal cities in the state presenting a permanent population of about 26,000 people. Half of its 8.4 km-long shore is developed (Table 1), mainly Praia Grande and Praia da Cal. Beachfront properties consists in single-family houses although larger buildings are observed one or two blocks from the beach. Landscaping works using exotic and native plants are observed along part of the Prainha and Praia da Cal. Undeveloped shores include Guarita (Figure 3a) that is inside a State Park and Itapeva that has already few houses and facilities built at the top of the dunes. Development, constructions on the dunes (houses, drink and food facilities, and sidewalks), the presence of a jetty, and landscaping contributed to include 63% of the Class 1 length into altered shorelines (Table 1).

Table 2.1. Classification of the Rio Grande do Sul shorelines according to the length of developed shorelines, urbanized dunes, afforestation, and altered (impacted) shores.

Class	Length	Urbanized Shores		Urbanized Dunes		Afforestation		Altered Shores	
Segment	km	km	%	km	%	km	%	km	%
1	8.4	4.2	50.0	0.5	6.0	0.3	3.6	5.3	63.1
2	10.9	5.1	46.8	0.8	7.3	0	0	10.9	100
Northern	126.2	100.0	79.2	51.1	40.5	47.4	37.6	97.8	77.5
Hermenegildo	2.5	2.5	100	2.5	100	0	0	2.5	100
Chuí	0.9	0.9	100	0.9	100	0	0	0.9	100
3	129.6	103.4	79.8	54.5	42.1	47.4	36.6	101.2	78.1
Central sector	266.2	10.4	3.9	10.4	3.9	59.3	22.3	35.3	13.3
Southeast	199.8	0	0	0.3	0.2	63.7	31.9	40.5	20.3
Southern	12.4	0.3	2.4	0.3	2.4	0	0	1.9	15.3
4	478.4	10.7	2.2	11.0	2.3	123.0	25.7	77.7	16.2
Total	627.3	123.4	19.7	66.8	10.6	170.7	27.2	195.1	31.1

Percentages are calculated for coastal segments total length.

Class 2: Impacted and Prograding Open Sandy Beaches

Class 2 includes Cassino and Querência beaches, an 11-km long shoreline (1.7% of the state shorelines) south of the Rio Grande jetty. This 4-km long jetty obstructs the longshore sediment transport to the north, prograding the updrift beaches. Cassino is the largest and most important beach in the southern coast, having about 40,000 permanent residents, many left the city to live in their former summerhouses evidencing the new trend on coastal development in the state. Developed shores comprise about 47% of the class length (Table 2.1) and consist mainly in one-store houses and few small buildings (up to four stores) placed behind the dune fields. Although the shore is prograding, dunes have been decreasing in size and often show storm scarps. In the urbanized area, dune fixation and reconstruction have been implemented. Periodically, muddy deposits originated from the suspended matter of the Patos Lagoon discharge cover the swash zone and part of the backshore, changing the morphodynamic conditions of this sandy shore. Such events have been registered since 1901, before the construction of the jetties, and the influence of human activities to this process in recent years still needs to be quantified.

Traffic on the beach is constant and very intense in summer months as beach dwellers park their cars near the swash zone forming a long and continuos line along more than 10 km. Local government is willing to place a road in the dune area to facilitate car access to the beach. Urbanized dune areas are observed in Querência and some old buildings were abandoned as dunes invaded them. There are not sewage treatment plants and many domestic effluents discharge into the creeks that flow to the beach, polluting water and sand mainly in the summer when more houses are occupied. Additionally, the presence of the long jetties results in a shoreline 100% altered (Table 2.1).

Class 3: Developed and Mainly Eroding Beaches

About 129.6 km of the state shorelines are included in Class 3, comprising highly urbanized (nearly 80% of its length) and altered (78%) beaches (Table 2.1). Urbanized dune areas are observed along 42% of this class shoreline length (or about half of its developed shores). There are three coastal segments in this class: (a) Northern, a 126-km long segment limited by Itapeva (Torres) in the north and Dunas Altas (Palmares do Sul) in the south, (b) Hermenegildo, a 2.5-km long urbanized beach located at the southern coast, about 12 km north of the border with Uruguay, and (c) Chuí, a small beach village (0.9-km long shoreline) at the southernmost end of the state, limited south by the Chuí jetty that has fixed the former migrating Chuí inlet which marks the Uruguayan border.

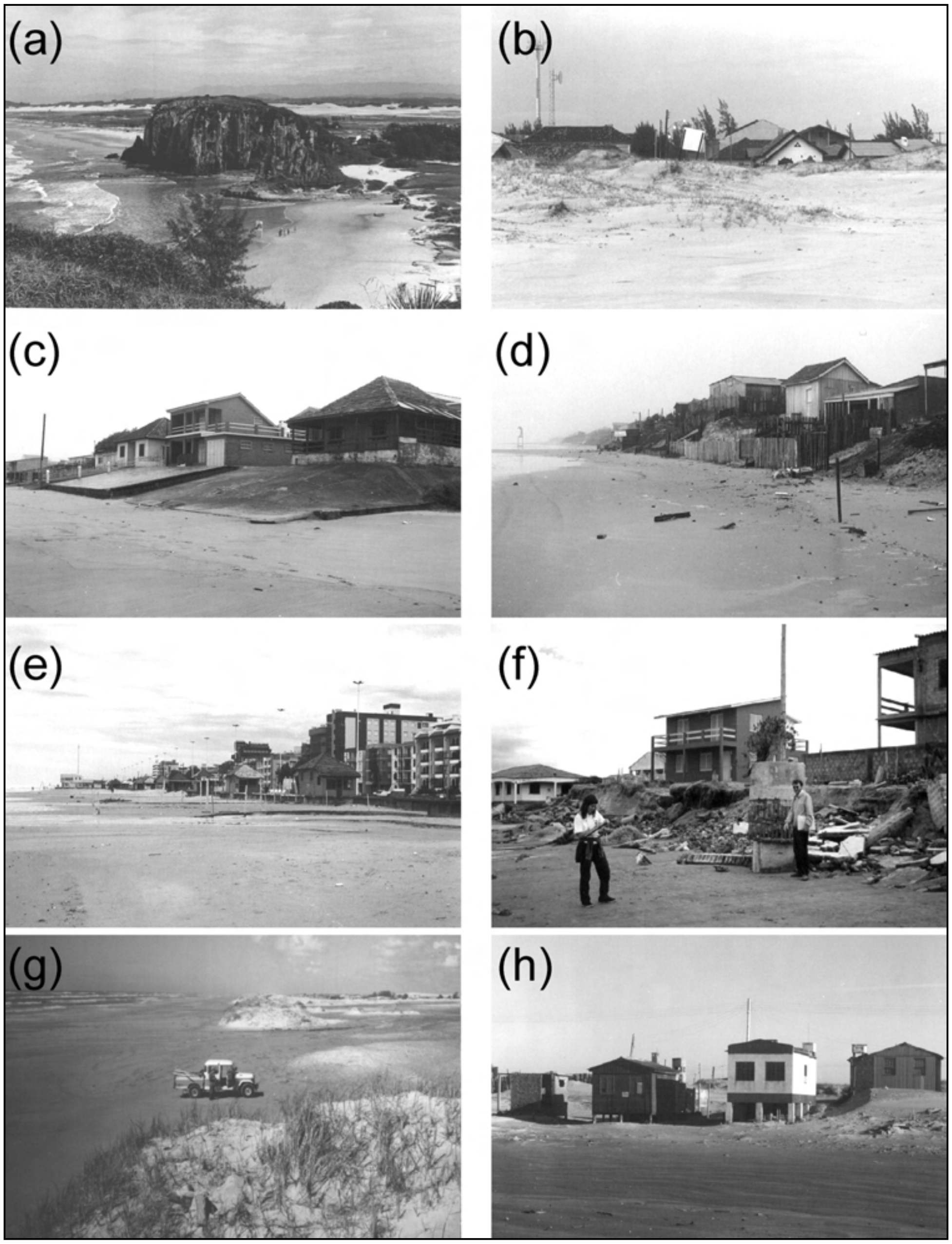

Figure 2.3. Pictures show examples of beachfront development in RS beaches. (a) Praia da Guarita (Torres) show the rocky headlands observed in the northernmost coastal sector (Class 1). (b) Single-family beachfront properties placed behind the dunes are the dominant type of urbanized shores in RS (Class 3). (c) Hard engineering structures are observed protecting houses built on top of the dunes mainly in the south of the northern sector (photo) and in Hermenegildo (Class 3). (d) An increasing problem has been small and wooden shacks built illegally on dune areas, as observed in Pinhal (Class 3). (e) Capão da Canoa represents the highly urbanized beaches of the area between Capão Novo and Tramandaí in the northern sector (Class 3). (f) Armored beachfront houses built on top of dunes in Hermenegildo have been threatened by wave attack and storm surges during storms (Class 3). (g) Undeveloped open sandy beaches dominate along 76% of the state shoreline (Class 4). (h) In some of the small beach villages present along the undeveloped central sector, houses were built on pilings to minimize the damages caused by migrating dunes (Class 4).

The Northern segment is the longest developed coastal segment and concentrates the great majority of the state coastal urban centers. Approximately 79% of its shoreline length is urbanized (Table 2.1), and the undeveloped shores usually consist in short sections (of about 0.3 to 0.5 km) that mark the limit between adjacent developed beaches. Beachfront development usually consists in one-family (one or two-store) houses placed behind the dunes. Thus, coastal urban areas consist mainly of small beach villages that have a very small permanent population and are occupied only in the summer months, except for few larger cities, such as Capão da Canoa and Tramandaí. These urban centers concentrate most of the services offered through out the year as they have a larger permanent population, and have shown an accelerated population growth in the last decade.

Several human-induced changes have been associated to urbanization: removal of the dunes to give place to beachfront properties, roads, and other facilities, pollution from domestic effluents, closure of natural washouts and creeks, and shore armoring. As a result, dunes are less developed or completely removed in urban areas, while undeveloped areas still show well-developed dunes. Revegetated dunes are observed in 37% of this shoreline, mainly as landscaping or in dune fixation and reconstruction works (*i.e.* Imbé and Atlântida Sul). Probably, anthropic changes, in addition to natural processes, have caused a negative sand balance that is evident in the areas where stormy conditions threatened coastal constructions placed on the dunes, such as in Cidreira and Pinhal (Figure 2.3c, d).

At the northern urbanized compartment, it is possible to further distinguish three segments according to the distribution and distance between developed beaches and the quality and location of beachfront properties. North of Capão Novo there are long undeveloped sections separating urbanized beaches, so this is the least developed shore in this segment. Probably, the greater distance from the metropolitan area of Porto Alegre (the state's capital) is the main factor that restrains occupation in this area. Beachfront properties are usually nice single-family houses (medium class) built behind the dune area (Figure 2.3b), resulting in the least altered section of this segment and more organized beach villages. The southernmost segment (Cidreira to the south) presents the most chaotic beachfront occupation. Beachfront properties were built on the top of the dunes and have been threatened by erosion during storms, leading to the implementation of protection structures, such as seawalls and revetments (Figure 2.3c). Some of the developed dune areas consist in small and poor wooden shacks illegally built (Figure 2.3d).This sector is about 80 km from Porto Alegre and presently has many permanent residents that left the metropolitan area to live by the sea. The central sector (from Capão Novo to Nova Tramandaí) consists in the most developed shores in the RS (Figure 2.3e). Beachfront properties consist in fancy multi-family resorts, high buildings, and high standard single-family houses. Along most of this shoreline, dunes were totally removed to give place to boardwalks or houses, food and drink facilities were built on the beach, and storm surges frequently threaten coastal constructions. Probably, the road built about ten years ago to link the beaches at the northern coast to the highway that starts in Porto Alegre contributed to the fast growing coastal cities in this area.

The other two segments consist in the urbanized shores of Hermenegildo and Chuí that are 2.5 km and 0.9 km long, respectively, inserted in the mainly undeveloped southern segment. They are 100% altered and urbanized beaches, mainly due to the presence of hard engineering structures in the armored shore of Hermenegildo and the jetty in the Chuí inlet. Beachfront properties in Hermenegildo were built on top of the dunes and have been threatened by erosion (Figure 2.3f), resembling the problems observed in the northern segment south of Cidreira. As a result, its shoreline is heavily armored as 61% of beachfront houses are protected (ESTEVES *et al.*, 1999). Storms frequently destroy coastal structures and people in Hermenegildo are already used to the endless cycle of rebuilding houses and structures year after year. In the other hand, although Chuí beach is located downdrift of the stabilized Chuí inlet, it is not experiencing a significant shoreline retreat, probably due to the short extension of the jetty. Additionally, the presence of a pleistocenic sandy barrier (locally known as Barrier III) near the shore might have some influence in the shoreline change rates as it supplies sand to adjacent beaches.

Class 4: Undeveloped Open Sandy Beaches

Undeveloped exposed beaches are the dominant coastal environment in the RS, comprising about 478 km (76%) of the state shoreline (Table 2.1). They are mainly fine sand beaches with vegetated frontal dunes that have not been impacted by human activities (Figure 2.3g). About 2% (10.4 km) of its shoreline is sparsely urbanized due to small fishing villages that are mainly built on the dunes. The impacted sections in this class consist in urbanized dune areas, the presence of *Pinus* sp. forests for commercial harvesting too close to the beach (sometimes in the dunes), and areas close to the urban centers of Class 2 and 3, totaling 16.2% of the 478.4 km (Table 2.1).

This class presents three segments: (a) the state's central coastal sector, a 266-km long shoreline from the East jetty at the Patos Lagoon inlet to Dunas Altas in the north, (b) southeast, 200 km of shorelines from Querência to Hermenegildo, and (c) southern, the 12.4 km of beaches in between Hermenegildo and Chuí. The central coastal segment presents the majority of the urbanized shores in this class that are mainly fishing villages. In some of these villages, migrating dunes invade the houses that have been built on pilings to minimize the damages (Figure 2.3h). In the southeast segment, beach traffic south of Querência and *Pinus* sp. afforestations are the main human impacts. About 15 km south of Querência, there is a 21-km long shoreline where dunes are well developed although they are discontinuous due to the presence of sand plains associated to large washouts. The southern segment is similar to the other two and presents one small village built up on the dunes.

Shorelines in Class 4 consist in long segments that are still undeveloped, mainly due to the long distance from inland urban centers and to the lack of roads. To most of these segments, the only access is driving through the beach and, as it is an open shore, there are no natural harbors for recreational or fishing boats. However, a new paved road that will cross the central shores up to São José do Norte linking these undeveloped shorelines to the northern urban centers, might change the present unoccupied areas in the near future as new settlements will probably be established.

DISCUSSION

Development along RS shorelines has been concentrated in the state northern coast, except for few urban areas and small fishing villages present in the southern and central coasts, respectively. Probably, the distance from larger inland urban centers and the facility of road access to the coast are the main factors contributing to the differences in development level along the state shorelines. The northern coast is close to the most densely populated areas of the state (the northeast region and Porto Alegre metropolitan area) and has the best roads. Access to the central coast, south of Quintão to São José do Norte, is very difficult as there are only two ways, driving on the beach or through the BR101, called the “Hell’s Road” along this part of the RS coast. It was an uneven dirty road almost impossible to be crossed, mainly after rainfalls. In the last two years, BR101 started to be paved and soon it will be connecting the beaches up to São José do Norte. It means that the paved road will facilitate access in a north-south direction through an almost completely undeveloped 270-km long shoreline. This shoreline consists in a sandy barrier that separates the Patos Lagoon from the Atlantic Ocean, so there is not east-west road connection to the rest of the state. Part of this area belongs to the National Park of Lagoa do Peixe, an important rest site for migrating birds. Thus, a brand new paved road associated with ecological attractions (*i.e.* coastal lagoons, National Park) will result in more people visiting the area. Small villages soon will have to offer infrastructure and services, permanent and temporary population will grow, and the consequences of a chaotic development may devastate this sensitive area in few years.

At present, situation on the southern coast is similar to the central coast. However, there is no evidence that in the near future it will be threatened by a development bloom as it is expected in the central coast. Except for the urbanized shores of Cassino, Chuí, and Hermenegildo, this coast is completely undeveloped, it is far away from any urban centers, and it can be reached only through the beach as there is no road access along about 200 km of shorelines. Due to the presence of large coastal lagoons (Mirim and Mangueira) and the small population in the southern region, characteristics along this shore might remain unchanged in the near future. Possibly, the only change the southern coast may experience is related to the Port of Rio Grande expansion. It is the third largest Brazilian port and the most important for the trade between MERCOSUL countries. The extension of both jetties (at present they are about 4-km long) and the deepening of the navigation channel are already scheduled to allow larger ships to anchor. If the port expands as expected, it might result in an accelerated growth in Cassino Beach as it is very close to the industrial district and the port itself.

As most of the state shorelines are undeveloped, the better alternative is to implement management policies according to the natural characteristics of specific coastal segments. For example, the central coast has a great potential for ecological tourism related to the National Park of Lagoa do Peixe or recreational fishing, and the development of urban centers might reduce this potential. Regulating future uses on undeveloped shores is the best and cheapest way of management, as it will avoid problem areas to spread through the entire coast when they become developed. Urbanized areas in the southern coast consist in short beach segments surrounded by long undeveloped shorelines. Thus, management strategies there might differ from the ones applied to the northern highly urbanized shores. For example, relocation or planned retreated should be evaluated as possible responses to the erosion problem in beaches such as Hermenegildo, where beachfront properties are not worth an expensive protection measure and there is enough undeveloped area either alongshore or inland. The same problem in the area from Capão da Canoa to Tramandaí should be addressed in a different way as beachfront properties are worth to be protected and there is no room for relocation.

Altered shores are mainly associated to human activities. Coastal development did not leave much space for the natural beach dynamics to take place; as a consequence, in several places it has been threatened by high-energy waves and storm surges during storms (Figure 2.3). Shore armoring, fixation of coastal dunes, and sand mining probably have contributed to a sand deficit in RS beaches. The artificial closure of natural washouts might be another anthropogenic change that tampers with local sand balance. In many coastal communities, washouts were artificially closed for road construction and tend to reopen temporarily during storms or high rainfall events, destroying nearby constructions. Coastal debris, fishing refuse, and city litter are observed along the entire RS coast. Surprisingly, debris (brought by natural washouts or by storm waves) causes a greater visual impact along unoccupied beaches, as along most of developed shorelines they are periodically cleaned. However, in the summer months, domestic effluents discharge a large amount of sewage in natural creeks that cross dunes and beach resulting in polluted sand and water along the highly urbanized areas. ISLA *et al.* (1998) presented a review of erosion problems caused or aggravated by stabilization of coastal dunes and concluded that fixation of dunes contributed to shoreline retreat in their study area. In the same way, growth of commercial woodlands in dune areas was considered a condition of human-induced alteration, although its contribution to the coastal sand deficit is still unknown.

CONCLUSIONS

According to the natural characteristics and human impacts, the RS shores can be grouped into four classes: (1) beaches under the influence of rocky headlands, (2) impacted and prograding beaches, (3) developed and mainly eroding beaches, and (4) undeveloped open beaches. Class 1 consists in the beaches of Torres (8.4 km), the only place where rocky headlands are observed. These beaches are developed and human-activities have impacted most of its shoreline that has shown a trend to accretion. Class 2 includes the urbanized and highly altered area of Cassino Beach (10.9 km), an open sandy beach that has been accreting due to the presence of a long jetty that obstructs the longshore sediment transport. Class 3 is a 129.6-km long shore segment comprised by developed sandy beaches that have been intensely altered due to human activities. Class 4 includes the undeveloped and least impacted sandy beaches that represent 76% of the state shoreline length.

In general, the state coast is mostly undeveloped except along one-fifth of its length, concentrated in the north where urban areas have the fastest growing populations in the state. Despite the long and undeveloped coastal segments, almost one-third of the state shorelines have been impacted by human activities, such as urbanization, constructions on the dunes, sand removal from the beaches and dunes, and commercial woodlands. Beaches in Class 3 represent what might be the consequences if fast growing coastal development continues in the same chaotic and unplanned way through the undeveloped areas. In the other hand, the long and undeveloped shore segments are a perfect environment for the application of a successful coastal management plan that will guide land uses and occupation and avoid the same critical problems observed in coastal urban centers at present.

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CAPÍTULO 3

LONG- AND SHORT-TERM COASTAL EROSION IN SOUTHERN BRAZIL

Esteves, L.S.; Toldo Jr., E.E.; Dillenburg, S.R. & Tomazelli, L.J. 2002. Long- and short-term coastal erosion in southern Brazil. *Journal of Coastal Research*, SI 36, 273-282.

ABSTRACT

Rio Grande do Sul is the southernmost state in Brazil. Open sandy beaches dominate the 630-km long shoreline that is 76% still undeveloped. Less than 5% of the state's population (totalling 9.7 million people) live in coastal cities. However, the coastal population is growing faster than the state's average since 1990. Although intense erosion is widely accepted along the beaches of Conceição lighthouse and Hermenegildo, the extent of erosion along the Rio Grande do Sul shoreline is still a controversial issue. Discussions arise from the contrasting results presented by studies addressing coastal erosion in Rio Grande do Sul. Recent DGPS monitoring indicates that about 80% of the Rio Grande do Sul shoreline is eroding; wave refraction studies indicate that it is mainly stable, and long-term coastal evolution modeling reveals a dominantly prograding shore for the last 5 ka. This work critically evaluates published data on long- and short-term causes of coastal erosion in Rio Grande do Sul, in an attempt to highlight the unanswered questions that could minimize the debate. The analysis includes sea-level rise, concentration of wave energy due to large-scale coastal topography, sand deficit as the long-term causes of erosion; storm surges, concentration of wave energy due to small-scale submerged features, interference in the longshore sediment transport, and human activities as the short-term causes. Discrepancies in shoreline change results are a matter of the temporal scale in question and what are the causes that play a significant role on it. For coastal management purposes short-time events represent a far greater hazard than long-term trends. It is therefore reasonable to state that in order to support decision-making mechanisms in Rio Grande do Sul, a better understanding of the relationship of storms, sand budget, and beach erosion is necessary.

Additional Index Words: Shoreline change, beach erosion, coastal evolution, Rio Grande do Sul

INTRODUCTION

Rio Grande do Sul is the southernmost state in Brazil (Figure 3.1) and its 630-km long shoreline is one of the least-developed in the country. In 1999, about 430,000 people were living in coastal cities, representing 4.4% of the state's population (9.9 million). However, the coastal population has grown about 1.5% per year since 1991 with six of the ten cities that had the greatest population growth in the last decade situated on the coast. Thus, a new trend of coastal occupation is evident and undeveloped areas will probably give way to new settlements in the near future. To avoid unplanned development along hazardous coastal segments, it is necessary to identify such areas and to understand the effects and interactions of coastal processes in different time scales, particularly those related to shoreline changes.

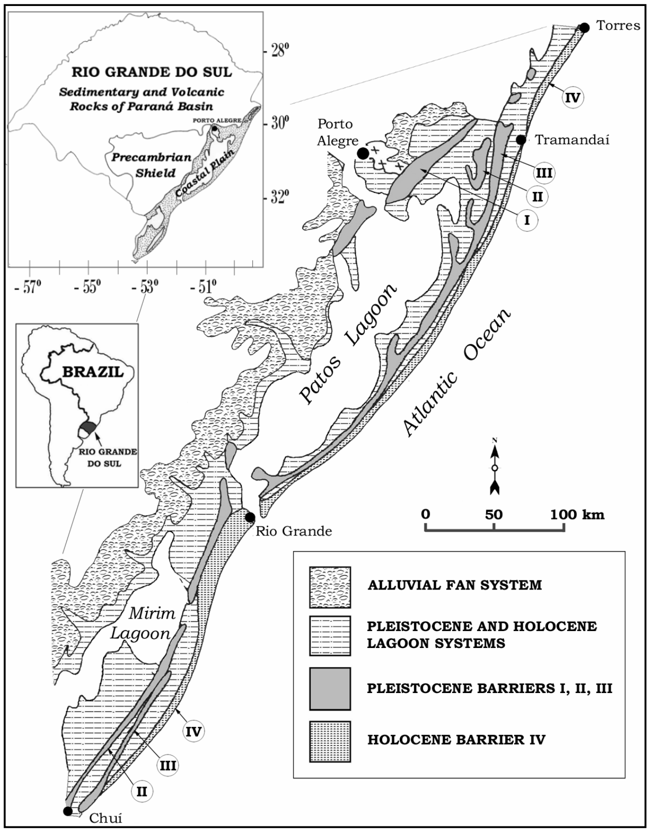

Figure 3.1. The study area consists in the 630-km long shoreline of Rio Grande do Sul, the southernmost state of Brazil.

As the Rio Grande do Sul shoreline is mainly undeveloped (except for the northern sector) and beaches are used only in the summer months when calm weather prevails, coastal studies have not attracted the attention of community, government, or indeed researchers until recently. Only in the late 1980s, published works started to focus on coastal processes, including those addressing beach erosion in Rio Grande do Sul (VILLWOCK and TOMAZELLI, 1989; TOMAZELLI, 1990); before that, articles on coastal studies were mainly descriptive. Since then, several studies have addressed coastal erosion in Rio Grande do Sul indicating natural and human-induced contributing factors in the long-term (*i.e.* TOMAZELLI *et al.*, 1998; TOMAZELLI and DILLENBURG, 1998; DILLENBURG *et al.*, 2000) and the short-term (*i.e.* CALLIARI *et al.*, 1998a,b; ESTEVES *et al.*, 2000a; TOLDO *et al.*, 1999). The increasing interest in coastal processes and shoreline changes reflects the intensification of coastal occupation and beach use, as well as the growing economic importance of beach-related tourism. Although knowledge about coastal processes in southern Brazil is improving, it is still incipient, and many unsolved issues need to be addressed. At present, there is an ongoing discussion on whether the Rio Grande do Sul shore is mainly eroding, prograding or stable.

This paper compiles available shoreline change data at different time scales, critically analysing them to help direct which logical step should be taken in the study of coastal changes in the state. Additionally, present shoreline monitoring results are discussed in an attempt to establish the present extension of beach erosion or at least identify shoreline change trends in Rio Grande do Sul.

STUDY AREA

The Rio Grande do Sul shore is part of a large coastal plain that extends between the granitic headlands of Cabo Polonio (Uruguay) in the south and Cape Santa Marta in the north. It is remarkable the presence of a well developed lagoon system formed by two large ones (Mirim in the south and Patos in the middle coastal sector) and several small others in the northern littoral. The Rio Grande do Sul shoreline is 630-km long mainly consisting of exposed fine sandy beaches that have a NE-SW general orientation. It is one of the longest sandy beach coastlines in the world, made up of only two permanent discontinuities (Tramandaí and Patos lagoon inlets). Innumerous permanent and temporary washouts discharge water accumulated behind the dunes, influencing the local sand balance.

Waves are the main hydrodynamic process along the Rio Grande do Sul coast, as the maximum tidal variation is less than 0.5 m (TOMAZELLI *et al.*, 1998). Winds from NE prevail and are mainly active during summer and spring; southerly winds are the strongest and more frequent during winter and fall. As southerly waves have higher energy, the net longshore sediment transport is to the north. Mean significant wave height is 1.5 m and mean period is 9 s. Storms associated to the passage of cold fronts frequently strike the coast in fall and winter months, mainly April and July (CALLIARI *et al.*, 1998b).

Generally, the Rio Grande do Sul coast can be subdivided into three sectors: (1) the northern sector comprised of 136 km of developed beaches extending from Torres (at the state border) to Dunas Altas in the south; (2) the central sector, 266-km long and includes the undeveloped beaches from Dunas Altas to the Patos Lagoon inlet, and (3) the southern sector made up of the shoreline from the Patos Lagoon inlet to the Chuí creek (at the border with Uruguay), a 225-km long shoreline with only 7.6 km of urbanized beaches (ESTEVES *et al.*, 2000b).

Well-sorted fine quartz sands dominate in the Rio Grande do Sul beaches (MARTINS, 1967), except in three areas: (1) south of the Conceição Lighthouse (central sector), where mean sizes are coarser and less sorted due to the presence of shell fragments; (2) in Cassino Beach, fine sediments from the Patos Lagoon cause a slightly decrease in the mean size, and (3) between

Albardão lighthouse and Hermenegildo (southern sector) there is a 30-km long segment (Concheiros do Albardão) that presents bimodal sediments composed by quartzose fine sands and bioclastic gravel (SIEGLE, 1996; CALLIARI and KLEIN, 1993). Morphodynamically, beaches vary from intermediate to dissipative stages, except along Concheiros do Albardão which was classified as reflective to intermediate according to CALLIARI and KLEIN (1993).

QUATERNARY COASTAL EVOLUTION

The geologic evolution of the Rio Grande do Sul coastal plain was described by VILLWOCK *et al.* (1986) and detailed in several following studies (*i.e.* VILLWOCK and TOMAZELLI, 1989, 1998; TOMAZELLI *et al.*, 2000). As the Quaternary coastal evolution was a key factor for the present shoreline configuration, this section summarizes the main findings of those studies.

The coastal plain comprises two major depositional systems formed by sea-level fluctuations in the Quaternary: the alluvial fan deposits that mark the western limit of the coastal plain and the barrier-lagoon systems developed seawards (TOMAZELLI *et al.*, 2000). The alluvial fan system consists of coarse-grained clastic deposits (gravel, sand, and mud) originated from gravity flows and accumulated at the base of highlands (sedimentary and volcanic rocks of the Paraná Basin to the north and the igneous and metamorphic rocks of the Precambrian shield in the south). Formation of these deposits probably dates from the late Pliocene regression to the Holocene and was controlled by climate changes. Arid periods might have intensified the formation of gravity flows, while water flows during the humid phases reworked the conical shape of individual fans into a continuous apron gently dipping seaward. Deposits at the edge of coalescent fans were eroded by higher sea levels in the Pleistocene resulting in marine and lagoon terraces that are particularly well developed and preserved to the south.

Four barrier-lagoon depositional systems were identified in the Rio Grande do Sul coastal plain, each representing the sedimentary record of a marine transgression, three during the Pleistocene and one in the Holocene (Figure 3.1). Each barrier represents the landward limit of the respective maximum transgressive event (VILLWOCK and TOMAZELLI, 1998; TOMAZELLI *et al.*, 2000). VILLWOCK *et al.* (1986) named the four barrier-lagoon systems as Barrier I (the oldest) to IV (the youngest). Absolute ages of the pleistocene barriers are still unknown (TOMAZELLI *et al.*, 2000). An attempt to correlate the last major peaks of the oxygen isotopic record and barrier formation indicates that they were probably formed in the last 400 ka (TOMAZELLI *et al.*, 2000). Barrier I, II, and III correlate with oxygen isotopic stage 11 (about 400 ka), stage 9 (325 ka), and sub-stage 5e (approximately 125 ka), respectively. Barrier IV was formed in the Holocene and corresponds to oxygen isotopic stage 1. About 18 ka ago, sea level was near the present shelf break and rose steadily up to 2-4 m above the present level at the maximum of the last transgression (about 5 ka BP). The following regression favoured the progradation of Barrier IV through the formation of beach/foredune ridges that were mainly developed in the smooth embayments in between Torres and Tramandaí and in Rio Grande (TOMAZELLI and DILLENBURG, 1998). The onshore sand transfer from the shelf was the main source for barrier progradation, as fluvial sands were retained in the lagoon system.

Figure 3.1 shows the location of the preserved barrier deposits. Barrier I is preserved in the northwestern part of the coastal plain as a 150 km-long and 10-km wide strip of aeolian sands at the top of basement highs. Barrier II is better preserved to the south, where it was responsible for the initial formation of the Mirim lagoon. Barrier III is preserved along most of the coastal plain extension and is formed by beach deposits covered by aeolian sands, demonstrating its regressive nature. Its beach deposits are rich in *Callichirus* sp. burrows, indicating an ancient high sea level at 6-8 m above the present. The Pleistocene lagoon systems (I, II, and III) developed in between the respective barrier (I, II, or III) and mainland (the previous barrier or the alluvial fan deposits). Barrier IV consists in the present shore deposits. The large lagoon system was developed in between Barrier IV and Barrier III at the maximum Holocene transgressive event. However, the last marine regression favoured the infilling of some lagoons that have evolved into lakes, swamps and floodplains.

EVIDENCE OF BEACH EROSION

The extent of erosion along Rio Grande do Sul beaches is a controversial issue. Some studies suggest that most of the coast is stable (*i.e.* CALLIARI *et al.*, 2000) and others indicate that it is mainly eroding (*i.e.* TOMAZELLI *et al.*, 1998; TOLDO *et al.*, 1999; ESTEVES *et al.*, 2001). However, intense erosion is widely accepted at the localities of Conceição lighthouse and Hermenegildo beach (CALLIARI *et al.*, 1998a, 2000; TOMAZELLI *et al.*, 1998).

Back-barrier lagoonal deposits and peat have been exposed at the beach along (a) the northern developed coastal sector in Jardim do Éden, (b) for more than 60 km continuously along the undeveloped shorelines of the central sector (in front and adjacent to Conceição lighthouse), and (c) in Hermenegildo beach in the southern sector (TOMAZELLI *et al.*, 1998). These lagoonal deposits show radiocarbon ages of 5.76 ka in Jardim do Éden (DILLENBURG, 1994), 3.49 ka close to Conceição lighthouse (DILLENBURG, personal communication), and 4.33 ka in Hermenegildo (TOMAZELLI *et al.*, 1998).

Foredune scarps in front of the Conceição lighthouse have retreated in an average rate of 2.5 m/yr in the period 1975-1995 (TOMAZELLI *et al.*, 1998). The analysis of beach profiles from 1996 to 1999 shows an average retreat rate of 3.6 m/yr for the same area and 1 m/yr for Lagamarzinho beach, about 70 km north of Conceição lighthouse (BARLETTA and CALLIARI, 2000). This lighthouse actually fell under wave attack during a storm in 1993. Destruction of coastal structures during storms has been a strong source of evidence of erosion in Hermenegildo. Beachfront owners have built seawalls and revetments to protect their properties from wave attacks and storm surges and yet have seen destruction not only of the armouring but also of the houses that were supposedly protected (ESTEVES *et al.*, 2000a).

LONG-TERM CAUSES OF EROSION

Relative Sea-level Rise

Geomorphological, sedimentological, and geochronological available data indicate that a sea-level fall has promoted progradation of the Rio Grande do Sul coast since the maximum of the last post-glacial marine transgression. Sea-level curves established for the Brazilian coast show a marine regression for the last 5 ka (SUGUIO *et al.*, 1985; ANGULO and LESSA, 1997). However, according to TOMAZELLI *et al.* (1998), the relative sea-level trend might have reversed at some point when progradation stopped and coastal retreat started. Although there is not enough data to build a consistent Holocene sea-level curve for the Rio Grande do Sul, the authors support their idea making an interesting statement that in this paper will be posed as a question. Where are the barrier deposits that associated with the (lagoon) peat and organic mud layers exposed at the present shoreline? Additionally, they conclude that short-term erosion due to storms is significant but can only result in long-term shoreline retreat if superimposed onto a longer-term mechanism, such as a sea-level rise.

The hypothesis of a rising sea level along the Rio Grande do Sul coast would be in agreement with the global trend of an eustatic rise in the order of about 1-2 mm/yr (*e.g.* DOUGLAS, 1991). Unfortunately, a long-term record of tidal levels along the Rio Grande do Sul coast does not exist. The nearest longer tidal record is from Puerto Quequén (Argentina), from where 64 years (1918-1981) of hourly tidal levels were analysed resulting in an average relative rise of 1.6 ± 0.1 mm/yr (LANFREDI *et al.*, 1998). Considering that this coast is part of a passive margin and there are no neotectonic movements, it is likely that the relative sea level is similar to the global trend. In the other hand, three studies show evidence that may conflict with this theory: the possibility of neotectonic activities in the Rio Grande do Sul during the Quaternary (FONSECA *et al.*, 2001), and vermetid tubes ^{14}C datings for nearby states which show a continuous regression for the last 5 ka with no evidence of levels below the present (ANGULO and LESSA, 1997; ANGULO *et al.*, 2001).

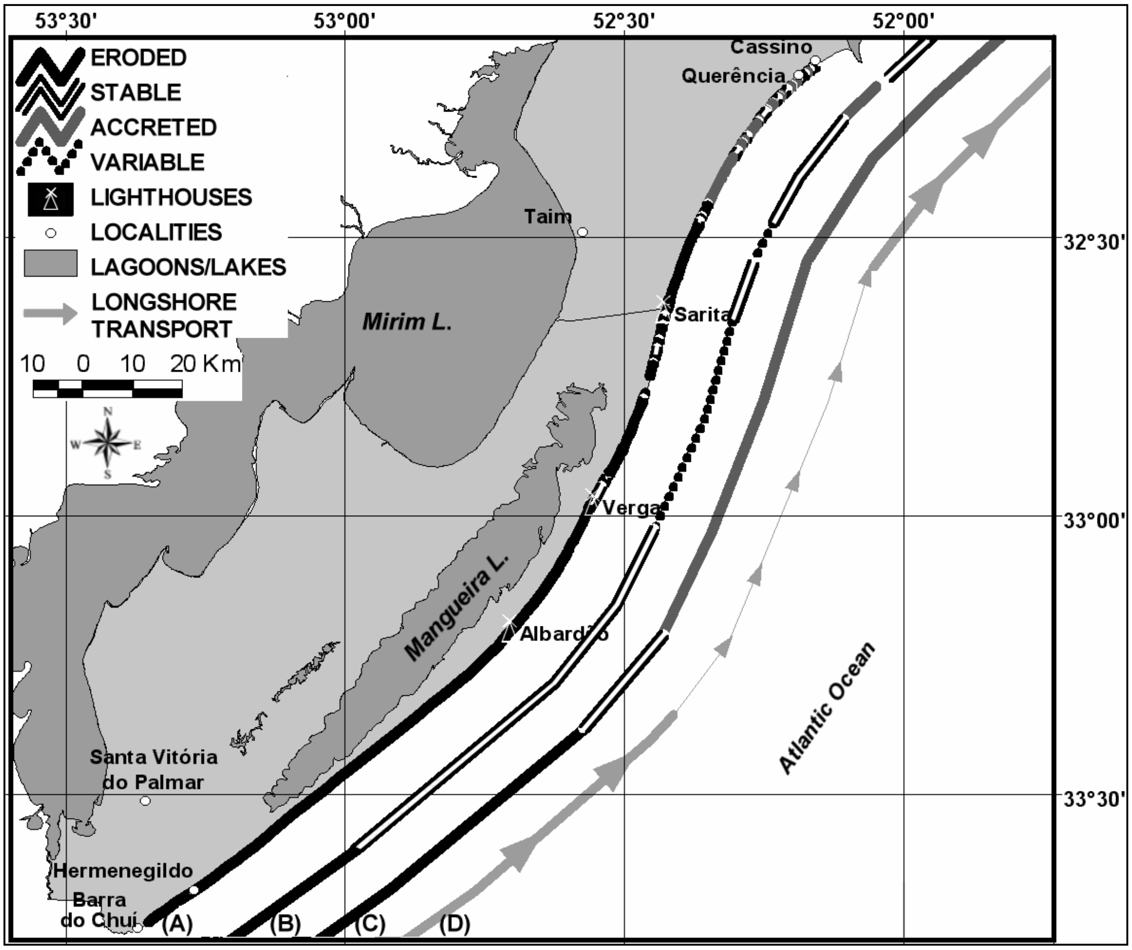

Figure 3.2. Shoreline changes in the southern RS littoral based on: (A) shoreline variations between 1975-2000 (ESTEVES *et al*., 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI *et al*., 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG *et al*., 2000). Arrows (D) show direction of littoral drift, and variations of longshore transport rates (as estimated by ALMEIDA *et al*., 2001) are indicated by changes in arrows width.

Concentration of Wave Energy Due To Large-Scale Coastal Topography

Shoreline configuration contributes to variations in the distribution of wave energy along the coast in a macro-scale (TOMAZELLI and DILLENBURG, 1998). Applying a coastal evolution model, DILLENBURG *et al.* (2000) suggested that antecedent topography was a key-factor for the definition of the present Rio Grande do Sul coastal shape that in turn have controlled the type of barrier that was developed. Steeper topography resulted in coastal projections and milder gradients originated embayments. Thus, concentration of wave energy in large protruding shore segments favoured development of retrogradational barriers, while progradational barriers were formed in smooth embayments. This mechanism explains why sedimentary records of progradation are evident only in parts of the coast and not evenly distributed, as it should be if a change in sea level was the only cause of shoreline changes. Classification of long-term shoreline changes based on DILLENBURG *et al.* (2000) is displayed in Figures 3.2, 3.3, and 3.4. Progradational barriers occur along about 40% of the state's coast, receded barriers along 34%, and 26% are classified as stable barriers.

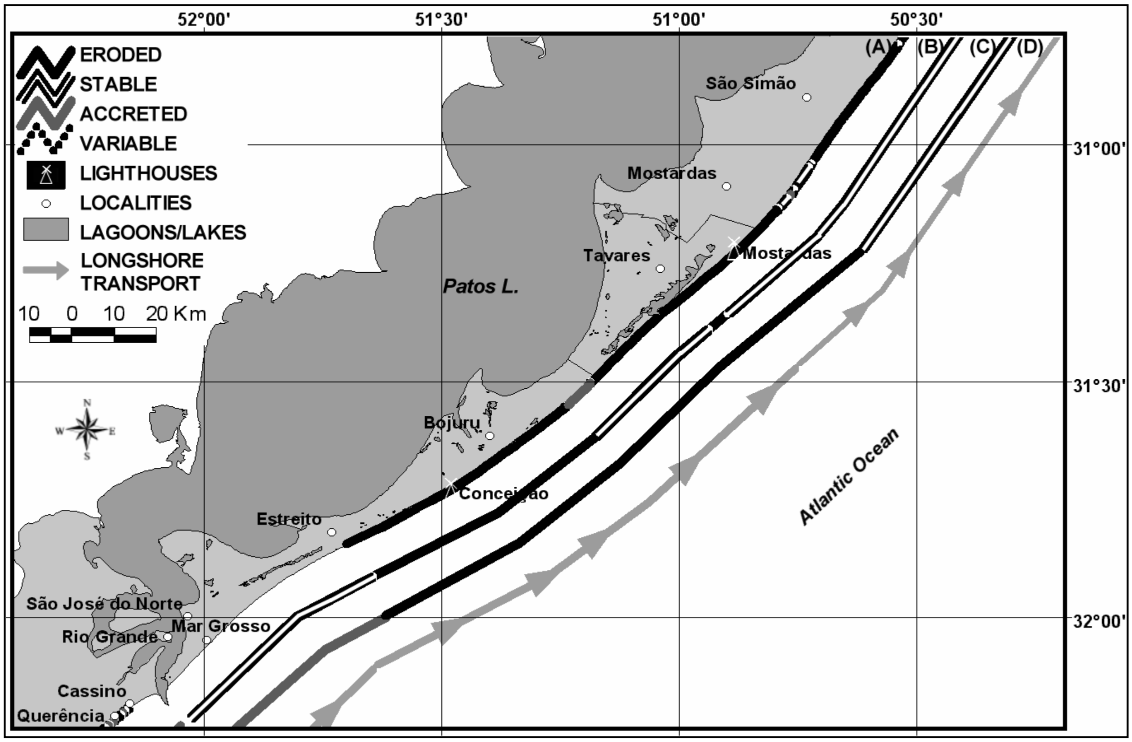

Figure 3.3. Shoreline changes in the central RS littoral based on: (A) shoreline variations between 1975-2000 (ESTEVES *et al.*, 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI *et al.*, 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG *et al.*, 2000). Arrows (D) show direction of littoral drift, and variations of longshore transport rates (as estimated by ALMEIDA *et al.*, 2001) are indicated by changes in arrows width.

Sand Deficit

The Rio Grande do Sul coast presents two large lagoons along the central (Patos lagoon) and southern coastal sectors (Mirim lagoon) and several other small lagoons and lakes along the northern littoral. This lagoon system traps sediment from fluvial discharge, reducing the sand volume reaching the shore (TOMAZELLI *et al.*, 1998). As such conditions exist since the formation of Barrier IV (last 5 ka), inland sand did not contribute to barrier growth. Two sources provided sand for progradation in the embayments: erosion of existing coastal landforms and onshore transport from the shelf. In the last 5 ka, the sand budget on the Rio Grande do Sul coast has been controlled by alongshore gradients of wave energy resulting from the concentration of wave rays in large-scale coastal projections (DILLENBURG *et al.*, 2000). Thus, a link between coastal morphology, wave energy gradients, and imbalances on sand budget is evident.

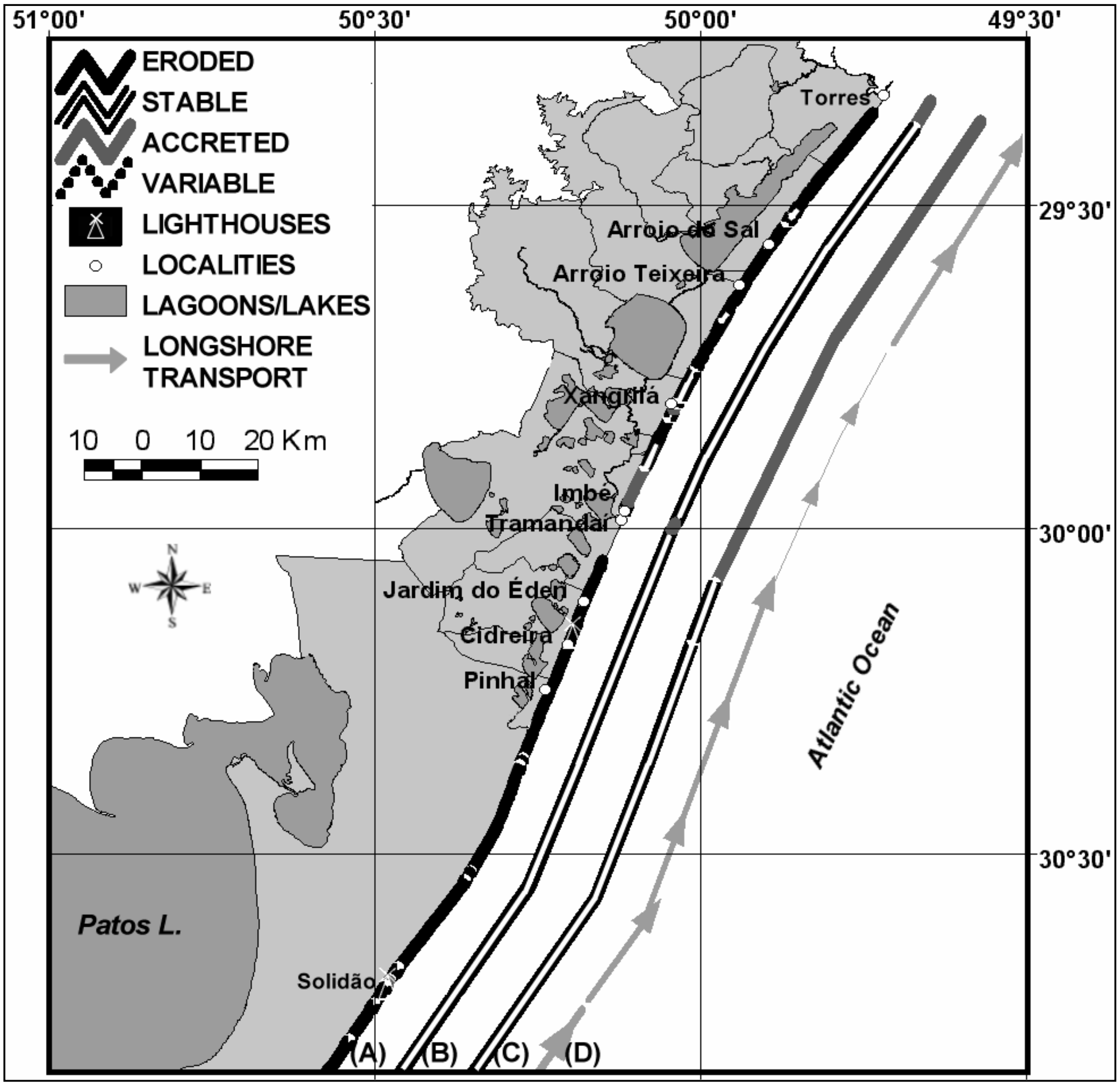

Figure 3.4. Shoreline changes in the northern Rio Grande do Sul littoral based on: (A) shoreline variations between 1975-2000 (ESTEVES *et al*., 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI *et al*., 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG *et al*., 2000). Arrows (D) show direction of littoral drift, and variations of longshore transport rates (as estimated by ALMEIDA *et al*., 2001) are indicated by changes in arrows width.

SHORT-TERM CAUSES OF EROSION

Storm Surges

Storm surges are described as the elevation in tidal level on top of the expected astronomical tide. In southern Brazil, they occur when S-SE winds force water onshore during the passage of intense cold fronts (forming cyclogenesis). Although storm surges are about 1-m high along the Rio Grande do Sul coast, the higher water level intensifies the erosive capacity of storm waves, causing severe damage at the coast mainly when coincident with high spring tides (CALLIARI *et al.*, 1998b). This catastrophic combination is more frequent in April and May and is more destructive the longer it lasts (CALLIARI *et al.*, 1998b). It is also known that the frequency of storms is a factor that influences beach erosion.

Studies addressing the occurrence and impact of storm surges in Brazil are scarce and limited to the monitoring of individual events. A few examples are the storms of July 14, 1993 and April 19-21, 1995 (CALLIARI *et al.*, 1998b), April 3-5 and 24-26, 1997 (BARLETTA *et al.*, 1999), and April 16, 1999 (ESTEVES *et al.*, 2000a). The 1993 and the 1999 storms were very similar and consisted of extratropical cyclones formed after the passage of a cold front striking the Rio Grande do Sul coast with average wind velocities of about 75 km/h, resulting in a storm surge of 1.3 m and 0.8 m (measured at the Rio Grande Port), respectively. Beach profile measurements showed that the 1993 and 1999 storms caused subaerial beach erosion in Hermenegildo of up to 60 m^3/m and 45 m^3/m, respectively. TOZZI and CALLIARI (2000) observed that maximum changes in sand volume occur when the first fall storms (from March to June) erode the accreted profile built during the summer months (from December to March). According to Tozzi's results, the storm of April 1999 was a typical example of the high-energy events that threaten Hermenegildo at least once a year. From data presented in BRITTO and SARAIVA (1999), the number of cold fronts passages along the Rio Grande do Sul coast in the winter months (June to August) from 1988 to 1998 varied from 6 to 14, with a mean of 10 for that period. However, there is still a lack of studies that examine storm distribution and frequency, related storm surges and beach profile responses in a longer term (*i.e.* do they fully recover?).

Concentration of Wave Energy Due to Submerged Small-Scale Features

Recent studies have shown that convergence of wave rays due to refraction on small-scale changes in bathymetry concentrates wave energy along the coast and is a probable cause of erosion in the areas of Conceição lighthouse and Hermenegildo (CALLIARI *et al.*, 1998a, 2000). According to these studies, convergence patterns in those two areas were identified for waves with periods longer than 9 s approaching from SSE-SW while a divergent pattern is observed in the northern shores. SPERANSKI and CALLIARI (2000) suggest that wave 'focus' is the major cause of erosion in the Conceição lighthouse area and in Hermenegildo. However, this mechanism could not explain erosion in Lagamarzinho, where BARLETTA and CALLIARI (2000) have estimated a retreat rate of 1m/yr. This 'unexplained' erosion indicates that other factors are actively contributing to erosion along the Rio Grande do Sul shoreline. Distribution of eroded, stable, and accreted shorelines according to the wave refraction patterns (CALLIARI *et al.*, 2000) is presented in Figures 3.2, 3.3, and 3.4. About 75% of the Rio Grande do Sul coast would be stable, 15% under erosion, 2% accreting, and 8% show a variable response to wave refraction.

Longshore Sediment Transport

Sedimentary and geomorphologic evidences indicate that net longshore transport is towards the north (*i.e.* accretion of beaches south of jetties). However, measures of longshore transport rates are still lacking for the Rio Grande do Sul coast. A recent study applied the Energy Flux Method (USACE, 1984) to estimate the potential littoral drift based on wave measurements in deep water (ALMEIDA *et al.*, 2001). Results indicate that the highest rates occur in the areas where intense erosion was observed. While the average rate for other coastal sectors is about 700,000 m^3/yr, they are in the order of 1.8 million m^3/yr from Hermenegildo to Albardão lighthouse and 1.6 million m^3/yr from Cassino Beach to Solidão lighthouse (ALMEIDA *et al.*, 2001). Thus, highest longshore transport rates are expected along the most intensely eroded beaches in the state, as can be observed in figures 3.2 and 3.3.

According to the results of ALMEIDA *et al.* (2001), it is evident that shoreline orientation has an important role on the littoral drift along the Rio Grande do Sul shoreline, where the highest rates occur in the southern half of coastal projections (shoreline orientation close to N45°E). Thus, long-term erosion in coastal projections may have resulted from higher wave energy due to wave focusing and steeper gradients, as pointed by DILLENBURG *et al.* (2000), and also due to appropriate angles of wave attack.

Human Activities

Despite the long and undeveloped coastal segments, almost one-third of the state shorelines have been impacted by human activities, such as urbanisation in active dune areas, shore armouring, sand mining, and construction of jetties (ESTEVES *et al.*, 2000b). Anthropogenic changes might be affecting local sand balance in a way that intensifies natural shoreline changes. For example, fixation of the Patos lagoon inlet by two 4-km long jetties resulted in accelerated accretion of the southern beaches due to obstruction of the longshore sediment transport. This coastal sector has shown long-term progradation (DILLENBURG *et al.*, 2000). In Hermenegildo, urbanization in the active beach/dune system and coastal armouring appears to have aggravated erosion along a long-term retreating shoreline. Coastal development did not leave much space for natural beach dynamics to take place, which has increased the risk of structural damage during storms (*e.g.* Cidreira, Pinhal, Hermenegildo). The artificial closure of natural washouts might be another anthropogenic change that interferes with the local sediment balance. In many coastal communities, washouts were artificially closed for road construction and tend to reopen temporarily during high rainfall events. Sand from the dune/beach system has been used for landfill and civil engineering purposes for a long time and, in some places, resulted in the removal of entire dunes. Although the impact of human activities on the sediment balance is still unknown, it seems to play a role largely at a local level, enhancing natural trends rather than reversing them.

DISCUSSION

According to TOMAZELLI *et al.* (1998), TOLDO *et al.* (1999), and ESTEVES *et al.* (2001), the Rio Grande do Sul shoreline is mainly eroding. CALLIARI *et al.* (2000) has stated that most of the Rio Grande do Sul coast is stable and does not show evidence of permanent natural erosion. It is possible that all these studies are correct under certain aspects. Figures 3.2, 3.3, and 3.4 display shoreline changes in the northern, central, and southern coastal sectors, respectively, according to: (A) shoreline variations between 1975-2000 (ESTEVES *et al.*, 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI *et al.*, 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG *et al.*, 2000). Additionally, it shows variation in the longshore transport rates (D) estimated by ALMEIDA *et al.* (2001).

Although these studies represent short (A and B) and long-term (C) changes resulting from different variables, all have shown erosion along the shoreline of the Conceição lighthouse (Figure 3.3) and Hermenegildo (Figure 3.4). There is also a reasonable agreement about the stable condition of a short segment north of Mostardas (Figure 3.3). Apart from that, results differ for one or all three studies, as in C the coast is dominantly prograding (40% of the shoreline length), in B is mainly stable (75%), and in A is mostly eroded (80%). These contrasting results can be explained by the difference in time-scales and in the variables analysed. Short-time oscillations can be superposed to long-term trends, masking them when only few years of data are analysed. Thus, shorelines that have been prograding for thousands of years may retreat in shorter intervals. In a life-long period, the effects of short-term events are easily observed while long-term trends might not be evident, unless change rates are extremely high. In this time frame, variables with slower reaction times (glacioeustasy, tectonoeustay, geoidal variations, isostasy) are not significant, leaving mainly hydrodynamic changes to be considered (FAIRBRIDGE, 1989). In the other hand, for longer-time intervals (*e.g.* 500 years), glacioeustasy and steric effects can cause a fluctuation of up to 30 cm in the sea level, besides the effects of isostasy (FAIRBRIDGE, 1989). Differences in the amplitude of changes caused by each variable in different time scales may explain the contrasting results of shoreline change studies in Rio Grande do Sul.

Coastal changes result from the interaction of several processes, natural and human, of long and short duration. When major variables act in the same direction (accretion or erosion), they enhance each others effects, then net variations are clearly identified. This is the probable scenario for the intensely eroded areas of Hermenegildo and Conceição lighthouse, where concentration of the wave rays occur at a long-term receded barrier, the shoreline orientation is highly susceptible to the southerly storm waves, and high longshore transport rates may be contributing to a local sand deficit, in addition to a probable rise in sea level. In places where major factors operate in opposition to each other, changes are variable and are a function of the time interval analysed. This might be the case for the northern coastal sector, where human activities and a relative sea-level rise oppose to the spreading of wave energy along a long-term prograding shore. So, some factors can be of major importance to changes in some shorelines and be indistinct in others. According to FAIRBRIDGE (1989), in places of adequate sand supply, without human interference, and where neotectonics is positive or neutral, beach equilibrium will be maintained in a scenario of a mean sea-level rise as high as 5-10 mm/yr. In contrast, the same rise in sea level and neotectonic settings in a low-relief shore without adequate sand supply will result in significant coastal retreat. This might be the case of the receded barriers developed along the large-scale coastal projections simultaneously to the shore progradation along the embayments suggested for the last 5 ka in Rio Grande do Sul (DILLENBURG *et al.*, 2000).

Short-term shoreline changes affect beach uses and can be potentially destructive in developed areas. Short-time events that last few days and have a frequent recurrence (within several months) represent a far greater hazard than long-term trends (FAIRBRIDGE, 1989). Therefore, knowledge of long-term trends is necessary to establish adequate coastal management plans, although they can only be efficient when maximum variations of short-term changes are properly incorporated. For management purposes, much needs to be done to evaluate the influence of different causative factors in the short and long time frame. It is evident that storms (strong winds, high energy waves, and storm surges) erode Rio Grande do Sul beaches. However, how long beach profiles take to recover? Do storms cause long-term local negative sand balance? Is it true that destructive storms strike the Rio Grande do Sul coast once a year or is that abnormally occurring only in the last years? How much sand is actually transported alongshore? Is sea level really rising in southern Brazil? If so, when did it start to rise and what are the rates?

CONCLUSIONS

All studies indicate erosion of the beaches of Conceição lighthouse and Hermenegildo, while diverse results are observed along most of the Rio Grande do Sul shoreline. Where long- and short-term causes lead to shoreline changes to the same direction, the net result is evident at all temporal scales. However, in places where at least one variable results in movement to the opposite direction, the net variation is reduced and might not be observed in different time scales. Thus, results obtained from shoreline change studies vary according to the temporal scale in question and the causes that are significant in that period. Although there is strong evidence of short- and long-term erosion spread along the Rio Grande do Sul shore, more data is necessary to define and quantify shoreline change trends. For coastal management purposes short-time events represent a far greater hazard than long-term trends. Hence, it is necessary to better understand the relationship between storms, sand budget, and beach erosion in Rio Grande do Sul to support proper decision-making processes.

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CAPÍTULO 4

ALONGSHORE PATTERNS OF SHORELINE MOVEMENTS IN SOUTHERN BRAZIL

Esteves, L.S.; Dillenburg, S.R. & Toldo Jr., E.E. 2004. Alongshore patterns of shoreline movements in southern Brazil. *Journal of Coastal Research*, SI 39, (no prelo).

ABSTRACT

Rio Grande do Sul has a 630-km long shoreline dominated by mostly continuous, exposed sandy beaches that are often described as straight and homogeneous. From 1997 to 2002, the state shoreline was mapped five times using the kinematic Global Positioning System method, showing regional differences in the dynamics of shoreline displacements. This study compares short-term changes with long and medium-term trends in coastal evolution. Generally, patterns of annual shoreline displacements are distinct for the three coastal sectors. Similar magnitudes and directions of changes occur along the southern sector, while displacements are to opposite directions in other areas. The effects of the high-energy winter conditions are evident in the landward displacements registered from Nov/1999 to Jun/2000. Similarly, the changes observed from Jun/2000 to Apr/2002 represent the recovery of the beach width from a post-winter to post-summer condition. A mirror image has been observed in between displacement lines of different time intervals for distinct coastal sectors, indicating that the return to a previous shoreline configuration and, perhaps, to its original position, is just a matter of time. Although these findings refer only to short-time scales, in the longer term, shoreline shapes may be continually recurrent while moving landward or seaward. Shoreline change rates obtained from aerial photographs show that the northern beaches are mainly prograding in the medium-term, with rates decreasing southwards, in the same way it was observed for the Holocene evolution. Shifts in the short-term trends are spatially coincident with changes observed in the long-term and in the dynamics of the transgressive dune fields.

Additional Index Words: beach erosion, DGPS, Rio Grande do Sul.

INTRODUCTION

The knowledge of beach and shoreline changes in Rio Grande do Sul is generally limited in time and space. Coastal data have been obtained in few places that are distant from each other, and are, at best, discontinuously available in the last 10 or 15 years. The coastline of Rio Grande do Sul is 630-km long and comprises one of the longest continuous sandy shores in the world. The visual similarity of its beaches and the lack of data to continuously represent long segments lead researches often to describe this coast as straight and very homogeneous. However, recent studies have shown that this coast is not straight and shows local and regional morphodynamic differences at various time scales (DILLENBURG *et al.*, 2000; ESTEVES *et al.*, 2002, 2003a).

From 1997 to 2002, the Rio Grande do Sul shoreline was mapped five times using the kinematic Global Positioning System (GPS) method in an effort to follow the trends in recent shoreline change studies, which have focused in gathering continuous data at a regional scale. Although only 20% of the state shoreline are developed, the coastal population has grown faster in the last decade and some pristine areas are already under threat of unplanned occupation (ESTEVES *et al.*, 2003b). A better understanding of the shoreline dynamics at various time scales is urgently required to support regional and local coastal management plans. This study describes magnitudes and patterns of short-term shoreline changes, focusing in the regional alongshore differences. Additionally, the short-term patterns are compared with medium-term rates obtained from aerial photos (from 1974, 1989, and 2000) and from evidence of the Holocene evolution of coastal barriers in an attempt to better understand shoreline changes in Rio Grande do Sul.

STUDY AREA

Rio Grande do Sul is the southernmost state in Brazil, sited around latitudes 27°S to 34°S and longitudes 50°W to 57°W (Figure 4.1), presenting a humid temperate climate with warm to hot temperatures in summer (mean of 26ºC) and cool temperatures in winter (mean of 12ºC). About 450,000 people live in coastal cities, or less than 4.5% of the state's population (ESTEVES *et al.*, 2003b). The majority of the developed areas is concentrated along the northernmost 120 km, comprised mainly by second houses that are occupied only in the summer months, when about 2 million people move to the coast (ESTEVES *et al.*, 2003b). The study area consists in the Rio Grande do Sul shoreline, where only two permanent discontinuities occur (Tramandaí and Patos lagoon inlets). The coast is usually divided into three major sectors: (1) the southern sector extends 220 km from the Chuí creek (at the Uruguayan border) to the Patos lagoon inlet (2) the central sector is a 290 km-long and mostly undeveloped shore, and (3) the northern sector, a 120-km long urbanized shoreline, extending from Quintão beach to the border with Santa Catarina state (Figure 4.1).

The RS coast is characterized by a complex system of coastal lakes and lagoons formed during the Quaternary sea-level fluctuations. In the last 5 ka, no new sand has been supplied to the shore from inland as the lagoon system retains the sands transported by the rivers (TOMAZELLI *et al.*, 1998). According to DILLENBURG *et al.* (2000), sand budget in the RS coast has been controlled by alongshore gradients of wave energy resulted from the concentration of wave rays in large-scale coastal projections and dissipation along smooth embayments. Northeast winds blow constantly along the shore, although southerly winds are the strongest and more frequent from April to July (fall and winter). Alongshore currents are bi-directional, but there is a net sediment transport to the north due to the strong southerly waves associated with the passage of cold fronts. This is a microtidal coast with tidal variation less than 0.5 m; consequently, waves are the main hydrodynamic process.

Intermediate beaches composed by well-sorted fine quartzose sands dominate in the RS (*e.g.* TOLDO Jr. *et al.*, 1993; CALLIARI and KLEIN, 1993; BARLETTA *et al.*, 1999), except along (a) the reflective to intermediate beaches of the *Concheiros do Albardão*, a 30-km long segment between Albardão lighthouse and Hermenegildo (southern sector), where bioclastic gravels are added to the quartzose fine sands forming a bimodal sediment, and (b) the dissipative beaches from Cassino Beach to Sarita Lighthouse (southern sector), where there is a slightly decrease in the mean grain size in the area of Cassino Beach caused by the suspended sediments carried through the Patos Lagoon mouth (CALLIARI and KLEIN, 1993).

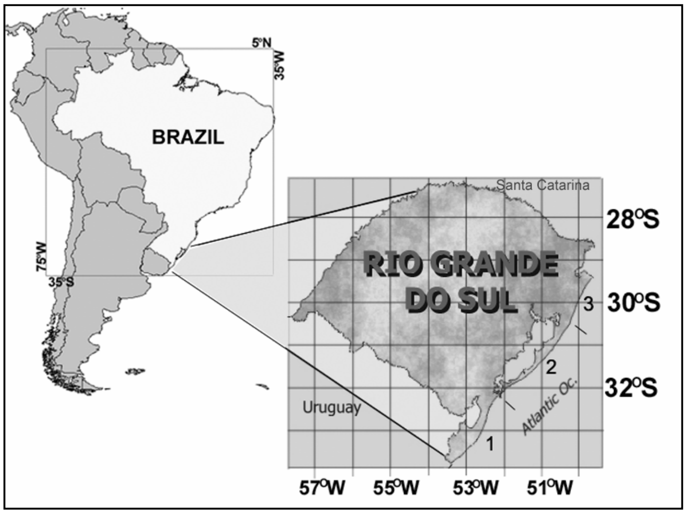

Figure 4.1. The Rio Grande do Sul shoreline is 630-km long and is usually subdivided in three major coastal sectors: (1) southern, (2) central, and (3) northern.

METHODS

From 1997 to 2002, the Rio Grande do Sul shoreline was mapped five times using the kinematic Global Positioning System (GPS) method (*i.e.* TOLDO Jr. *et al.*, 1999; MORTON *et al.*, 1993). The state beaches are flat, dissipative, continuous, and undeveloped, characteristics that favor the application of the kinematic GPS method to map the 630-km long shoreline in a fast and economic way. This study aims to compare shoreline positions mapped in 1997 (Nov/26-28th), 1998 (Nov/17-19th), 1999 (Nov/10-11 and 19th), 2000 (June/26-28th), and 2002 (April/15-17th) to determine regional differences in alongshore patterns of shoreline changes. Additionally, shoreline change rates were estimated from sets of vertical aerial photographs, and the long-term evolution of coastal barriers (during the Holocene) are analyzed to better understand coastal changes in the RS.

The aerial photographs used in this study were obtained in Jan/1974 and Feb/1989 (scale of 1:20.000) by the state *Departamento Autônomo de Estradas e Rodagens* (DAER), and in 2000 low altitude, small format, digital photographs were obtain by the Fundação Universidade Federal do Rio Grande (FURG) using the ADAR-1000 system (FONTOURA and HARTMANN, 2001). Distances between control points (at least 6 in each photograph) were measured to establish the error due to distortions and also due to the accuracy in identifying the exact points from where the measures were taken. Then, beach widths were measured every 150 m or 200 m in front of stable points along at least 2 km in five different beaches and the average rate of change was estimated for each one of the beaches.

In 1997, shoreline mapping was conducted using two Garmin GPS 100 Personal Surveyor; one was installed in a vehicle moving along the water line in an average velocity of 50 km/h to register positions every 5s, and the other was set in static mode every 100 km to enhance the horizontal accuracy to 3 m. In the following years, position data were corrected using a fixed GPS antenna. In 2000 and 2002, a Trimble GPS 4600 was used to register positions every 3s, resulting in an accuracy of 1 m. A major source of error in this study consists in the spatial and temporal waterline oscillations along the smooth slope of the RS beaches (1/30 in average). Such errors were minimized as mapping was always conducted on similar conditions (*e.g.* tidal levels, fair weather, no storms or passage of cold fronts in the weeks before field work). The waterline was chosen as the reference feature as it could be followed throughout the length of the study area and could be easily identified while driving along the beach. Dune crest or scarp, vegetation line, and berm crest are not continuous along the entire coast; then cannot be used to compare beach segments that are distant to each other. The high water line was the reference feature mapped in 2002, therefore a correction was necessary to allow this shoreline to be analyzed with the others. The correction consisted in displacing the shoreline mapped in 2002 seaward based on the distance from the high water line to the waterline measured on aerial photos obtained in 2000 and 1989. Such distances were measured every 200 m along several beaches, and the mean values were applied for segments with similar characteristics.

The ArcView GIS 3.2 program was used to display and organize the shoreline position data from where the ArcView extension Digital Shoreline Analysis System 2.0, developed by the U.S. Geological Survey (THIELER *et al.*, 2003), was applied to measure distances between mapped lines and to estimate shoreline change rates every 1 km alongshore for the regional analysis and every 250 m for the detailed analysis of the northern sector. Identification of regional patterns of shoreline displacement was based on line graphs of alongshore distance *vs.* shoreline change where a landward movement (shore retreat) was represented as negative values, and seaward movements (beach accretion) as positive values. Alongshore distance was measured from south to north, starting at the jetty of the Chuí creek (at the border with Uruguay) and ending at the beach of Itapeva in Torres. Although shoreline change rates are presented, they should not be interpreted as long-term trends as the time frame from the available data is too short. Rates were estimated to allow comparison between short and longer-term trends.

ALONGSHORE PATTERNS OF SHORELINE MOVEMENTS

Graphs of shoreline changes (Figure 4.2) indicate that shoreline movements occur differently along the three major coastal sectors of Rio Grande do Sul, including the maximum amplitude of displacements and the effects of seasonal and interannual changes (ESTEVES *et al.*, 2003a). Alongshore patterns of annual and seasonal changes are described below.

Annual Changes

Figure 4.2a represents annual changes in shoreline position as it shows displacements between Nov/1997-Nov/1998 and Nov/1998-Nov/1999. In general terms, magnitudes of changes and trends presented by both lines are similar along the southern sector, and to opposite directions in the central and northern sectors. Magnitudes of changes and shoreline mobility are greater along the central sector, where shoreline positions oscillate up to 140 m. Less variability is observed along the southern and northern sectors, where shoreline positions vary up to 50 m.

From Nov/1997 to Nov/1998, shoreline movements were exclusively seaward along the southern sector, indicating beach accretion with mean shoreline displacement of 25 m. From Nov/1998 to Nov/1999, similar behavior was observed, except in the southernmost 60 km where erosion was registered. Along the southern sector, the shoreline tends to move further seaward from south to north, oscillating around 20 m along the southern 90 km and reaching 50 m northwards (Figure 4.2a). This is partly due to the shoreline orientation, as the northern part of this sector is characterized by an embayment (*i.e.* favors deposition), and partly due to the long-term progradation of this coastal barrier (*i.e.* DILLENBURG *et al.*, 2000; ESTEVES *et al.*, 2003a). In the central sector, both annual lines (Nov/1997-Nov/1998 and Nov/1998-Nov/1999) show a wavy pattern alongshore (Figure 4.2a). They move seaward and landward to opposite directions and show regularly spaced peaks that do not always have same amplitudes. Magnitudes of changes are greater for the Nov/1997-Nov/1998 period, mainly for the seaward movements, resulting in a mean displacement around 22 m, while the mean for the Nov/1998-Nov/1999 line is 2.8 m. The cause of such wavy pattern is unknown, but preliminary analysis

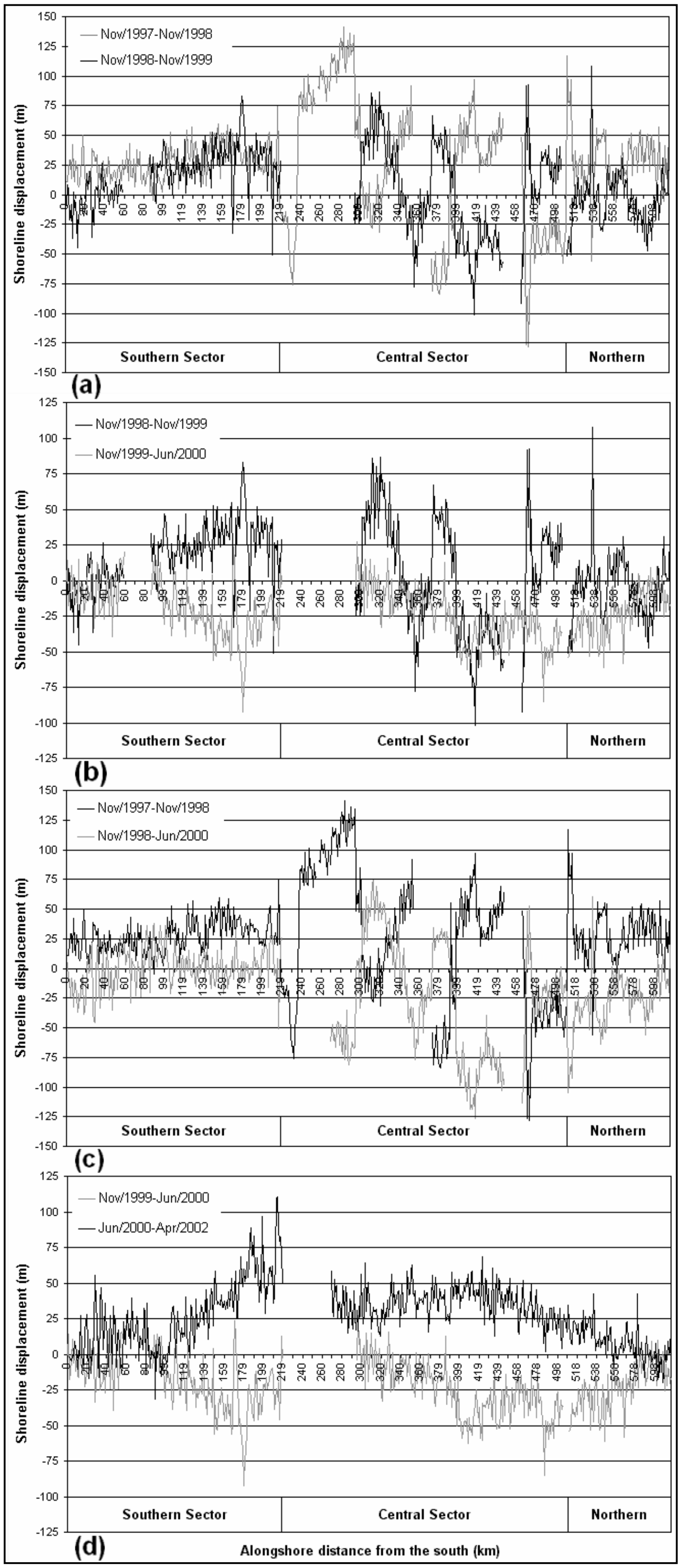

Figure 4.2. Line graphs comparing shoreline displacements to show alongshore differences in the patterns of annual changes (a) and in the seasonal effect (b, c, and d). Positive values represent seaward shoreline displacement and negative values represent landward movements.

indicates that it might be associated with smooth bulges and embayments on the shoreline configuration.

Annual lines also move to opposite directions along the northern sector. However, they do not oscillate from shoreward to landward displacements, as the Nov/1997-Nov/1998 line shows only beach accretion, and the Nov/1998-Nov/1999 line presents mainly erosion (Figure 4.2a). Shifts in the direction of the longshore current might be the main factor driving those lines to move to opposite direction in the period. The direction of the littoral drift has been visually registered three times a day at the fishing pier of Tramandaí since 1996 (NICOLODI *et al.*, 2000). The data show that the longshore current was dominantly flowing to SW in 1996 and 1997, shifting to NE in 1998 and 1999, returning to flow to SW in 2000, 2001, and 2002. Considering that the NE winds dominate along the Rio Grande do Sul coast, it is expected that the longshore currents flow in the NE-SW direction most of the time. However, the net longshore sand transport has been from SW to NE as the southerly waves are higher and more energetic. Taking into account that the net longshore transport is to the NE even when the main direction of the littoral drift is to SW, it is likely that sediment transport to the NE is more intense when the littoral drift flows dominantly to the same direction (*i.e.* 1998 and 1999). According to the data collected since 1996, in normal years, the longshore current flows to SW more than 60% of the time. It is assumed that, for such conditions, there is a balance in the volume of sediment transported alongshore as currents from the south are less frequent but stronger. When currents from south are dominant, a greater volume of sediment is probably mobilized from the areas with a shoreline orientation more exposed to the SSE waves where potential longshore transport is greater (LIMA *et al.*, 2001). These sediments are then transported north and deposited in the areas of less potential sediment transport, such as smooth embayments or along a segment of less exposed shoreline angle. Thus, the accretion registered in the northern sector from Nov/1997-Nov/1998 might be due to deposition of sediments eroded from beaches further south where alongshore sediment transport is more intense. The erosion registered in the following year is likely to represent the return of the shoreline to a more stable position as the ratio of SW and NE currents were already returning to normal. The reversal in the net direction of longshore currents is coincident with the strong El Niño event of 1997/1998. However, at this moment, no further investigation was conducted to evaluate the possible effects of El Niño in the coastal currents of Rio Grande do Sul.

Seasonal Changes

Seasonal effects on the patterns of shoreline movements were observed through the analysis of the changes registered between the shorelines mapped in November (1997, 1998, and

1999) and the ones mapped in June/2000 and April/2002. The effects of the higher energy conditions dominant in the fall and winter seasons can be observed in figure 4.2b. As expected, shoreline displacements in the period Nov/1999-Jun/2000 are mainly shoreward, indicating that an eroded condition prevails at the end of fall/beginning of winter along the three sectors. There is no evident rhythmic pattern alongshore in the Nov/1999-Jun/2000 line but a mirror image with the Nov/1998-Nov/1999 line is clear along the northern 130 km of the southern sector (Figure 4.2b). The spatial coincidence of peaks with similar magnitudes in opposite directions suggests that the shoreline returns to a pre-existing position along this segment. It implies also that the accretion registered in a one-year interval (from Nov/1998 to Nov/1999) was balanced by retreat in the following 7 months (or the next fall/winter season). Figure 4.2a shows that similar accretion was observed in the previous year (from Nov/1997 to Nov/1998). This raises the question whether such accretions are always balanced by retreat in the following winter or whether there is a net accretion in the short term that corroborates with the long-term progradation of the barrier.

Apart from the northern part of the southern sector, a mirror image was not observed in other areas for the period Nov/1998 to Jun/2000 (Figure 4.2b). However, such effect occurs along the northern sector when a longer period is considered (Figure 4.2c). The mirror image observed between the lines Nov/1997-Nov/1998 and Nov/1998-Jun/2000 indicates that the accretion over a period of one year was balanced by erosion 19 months later along the northern sector. A mean line derived from those lines shows a total recovery of the previous shoreline position from the Tramandaí inlet to Xangrilá, with a slightly negative balance southwards and a positive balance northward. In these areas, the beach width was not completely recovered because opposite peaks of displacements were not of the same magnitude. The mirror effect was also registered by LIST and FARRIS (1999) before and after a storm along the shores of Outer Banks (North Carolina, US) and Cape Cod (Massachusetts, US). The mirror image indicates that the shoreline has a memory of its original shape, to which it returns from time to time (LIST and FARRIS, 1999). Considering that the mirror image has been observed for different beaches on varied short-time scales (after passage of a storm, seasonally, and annually), the return to a previous shoreline configuration and, perhaps, to its original position, is just a matter of time. Maybe, an important question is whether such shape and position are dominant in time or represent only transitory moments in between a highly dynamic state.

In contrast to the Nov/1999-Jun/2000-line, the June/2000-April/2002 line shows accretion throughout the study area (Figure 4.2d). Such accretion was expected as this line compares a retreated beach registered at the end of the fall (June/2000) and a beach accreted by the fair-weather conditions that prevail in the summer (January to March). As in the Nov/1999-Jun/2000-line, the June/2000-April/2002 line does not show the regular wavy pattern observed alongshore in the annual lines (see Figure 4.2a) and also do not form a mirror image with any of the displacement lines obtained in this study. Although out of phase, the shape of the line and the magnitudes of changes are similar and opposed to the Nov/1999-Jun/2000 line (Figure 4.2d). Possibly, peaks of maximum shoreline variation travel alongshore according to seasonal changes in energetic conditions up to the moment where previous shoreline configuration and/or positions are re-established.

SHORELINE CHANGES IN THE LONGER TERM

To better understand changes along the state shoreline, a more detailed analysis was conducted for the northern sector, combining data of short-term changes (DGPS lines), rates estimated from aerial photos taken in 1974, 1989, and 2000, and evolution of coastal barriers in the Holocene. According to DILLENBURG *et al.* (2000), the coastal barrier had prograded from Torres to Tramandaí and remained stable from Tramandaí to Mostardas (central sector) during the Holocene (see Figure 4.3). Although the time interval of the DGPS monitoring is too short to provide consistent rates of changes, they were estimated just to compare the general alongshore trends with the ones observed in the Holocene. The shoreline change rates obtained for the period Nov/1997 to Apr/2002 show accretion from Torres to Xangrilá, stability to mild accretion from Xangrilá to Tramandaí, and erosion southwards up to Mostardas (Figure 4.3). Table 4.1 shows mean rates of changes estimated by linear regression that corroborate with these general trends. Cidreira is located south of Tramandaí and has been subjected to erosion (-4.5 m a^{-1}), Xangrilá has slightly accreted (0.7 m a^{-1}), and the other beaches located north of Xangrilá have accreted considerably (>1.0 m a^{-1}) from 1997 to 2002.

It is worth to note that Xangrilá is the place where there is a remarkable change in the width of the modern transgressive dune fields, which are narrow to the north and wider southwards, covering the entire Holocene barrier (DILLENBURG *et al.*, 2000; 2003). From Tramandaí to Mostardas, the transgressive dune fields are much wider and extend also on top of the Pleistocene barrier (DILLENBURG *et al.*, 2003), indicating a recent process of beach retreat (HESP, personal communication). Thus, trends of shoreline change obtained from the short-term data are more or less in accord with the observed behavior of present transgressive dune fields (Figure 4.3).

Comparison of aerial photographs for five urbanized beaches along the northern sector suggests that rates of change in the medium-term are highly variable alongshore, but agree well with the short-term trends (Figure 4.3). Measurements of shoreline positions were taken along 3 km in the area of Arroio do Sal, 5 km in the area of Curumim and Arroio Teixeira, 2 km in the area of Xangrilá, and 2 km in the area of Cidreira. Note that Cidreira is about 50 km south of

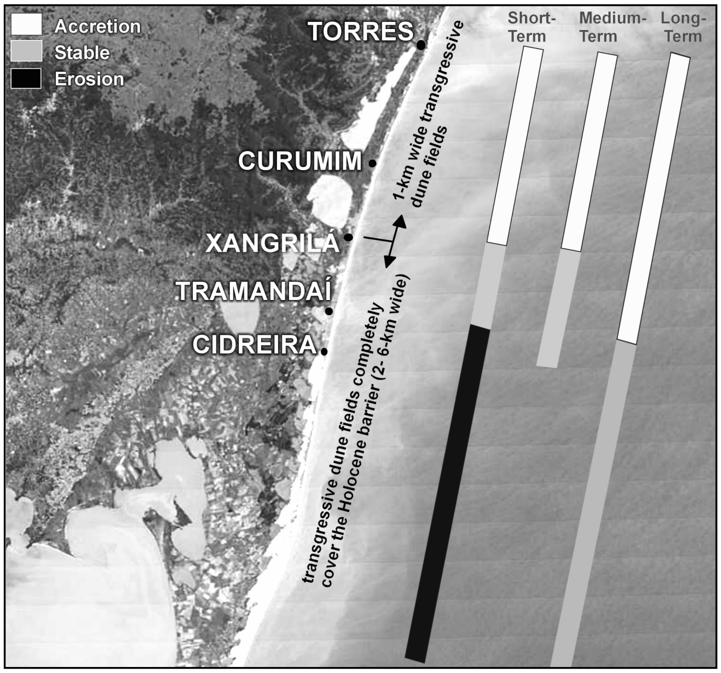

Figure 4.3. Shoreline changes in the short-term (1997-2002), medium-term (1974-2000), and long-term (Holocene) along the northern coastal sector of the Rio Grande do Sul. Aspects of the transgressive dune fields and the Holocene evolution were based on DILLENBURG *et al.* (2000, 2003).

Xangrilá that is 20 km south of Arroio Teixeira (less than 1 km apart from Curumim), which is about 15 km south of Arroio do Sal. Rates of changes will be presented as a range when the uncertainties of measurements affect the mean value estimated for each area. Shoreline change rates estimated from aerial photos and from the DGPS monitoring are presented in table 4.1.

It seems that the alongshore variability of shoreline changes is due to long-term gradients of wave energy caused by the shape of the shoreline and the steepness of the inner shelf (DILLENBURG *et al.*, 2003). Thus, higher energy (concentration of wave rays) tends to occur along convex shorelines adjacent to steeper inner shelf, and lower energy (dissipation of wave rays) is likely to occur along concave shores adjacent to a less steep shelf, favoring erosion and deposition, respectively. LIST and FARRIS (1999) have registered similar alongshore heterogeneity of shoreline changes along the Outer Banks (North Carolina, USA). It was observed that a complex pattern of accretion and erosion zones can be created as a result of high-angle waves approaching to the shoreline, *i.e.* when the angle that deep-water waves approach to the shoreline is greater than the one that maximizes longshore transport (ASHTON *et al.*, 2003). Although this process is still to be verified along the state’s shoreline, it is clear that the longshore sediment transport as a function of shoreline orientation is a major factor influencing alongshore variability of shoreline changes.

Table 4.1. Shoreline change rates estimated from aerial photos and DGPS shoreline monitoring.

	Cidreira ($m\ a^{-1}$)	Xangrilá ($m\ a^{-1}$)	Arroio Teixeira ($m\ a^{-1}$)	Curumim ($m\ a^{-1}$)	Arroio do Sal ($m\ a^{-1}$)
1974-1989	na	0.4	2.5	na	1.0
1989-2000	na	na	[b]	na	-1.9 a -1.4
1974-2000	0.7 a 0.9	na	1.4 a 2.6	3.0 a 3.4	-0.2 a 0.0
1997-2002[a]	-4.5	0.7	3.5	3.0	1.3

na: aerial photo not available for one of the dates

[a] Mean rate of change estimated by linear regression based on the DGPS monitoring

[b] Variation of the beach width was less than the errors due to measurements

It is clear from these data that the northern beaches are mainly prograding in the medium-term (Figure 4.3), with a trend of decreasing rates southwards, in the same way it has been described for the long-term coastal evolution. The area of Curumim/Arroio Teixeira has presented one of the largest progradation in the Rio Grande do Sul coast during the Holocene with rates around 2 - 3 $m\ a^{-1}$, similarly to the values obtained from the aerial photos for the period 1974 to 2000 (3.0 - 3.4 $m\ a^{-1}$ in Curumim, and 1.4 - 2.6 $m\ a^{-1}$ in Arroio Teixeira). In Xangrilá and Cidreira, measurements indicate lower rates of accretion than in the areas further north (Table 4.1). The variability of the rates obtained for different periods in the area of Arroio do Sal illustrates the oscillation from accreted to eroded phases that seems to be characteristic of the intermediate beaches of the Rio Grande do Sul. The shoreline fluctuates back and forth in the short-term while the coast progrades or retreats in the long-term. Such variability is probably due to a combination of factors, including interannual or decadal changes in wave climate, consequently in the volume and direction of alongshore transport, and effects of cyclic events such as El Niño/La Niña.

A recent trend of shoreline retreat in a long-term prograding coast was also registered along the Brittany beaches, in the Atlantic coast of France (BATTIAU-QUENEY *et al.*, 2003) and along part of the NW coast of England (PYE, 1990). The recent erosion along that part of the French coast is attributed to the depletion of sand reserves accumulated on the shoreface since the post-glacial marine transgression (PASKOFF, 1998 *in* BATTIAU-QUENEY *et al.*, 2003). This might be a factor to be considered also for the Rio Grande do Sul coast, where sand deposited on the adjacent shelf have been reworked to form coastal barriers in the last 5 ka (see DILLENBURG *et al.*, 2000) and no new sand have been supplied to the shore since then (TOMAZELLI *et al.*, 1998).

CONCLUSIONS

Data from DGPS monitoring of the shoreline indicate that shoreline movements respond differently to seasonal, annual, and interannual changes along the three major coastal sectors of Rio Grande do Sul. Differences include the amplitude of changes, the time frame in which beach widths are recovered, and the alongshore patterns of change due to seasonal and annual effects. From these findings, it is possible to conclude that, in a regional scale, the Rio Grande do Sul coast is neither straight nor homogeneous. The high alongshore variability of shoreline change rates is probably due to differences in the alongshore sediment transport resulted from changes in the shoreline orientation. The analysis of short-term changes (5 years), medium-term average rates (26 years), and the trends of coastal evolution in the Holocene indicates that beaches along the northern coastal sector of Rio Grande do Sul are prograding north of Xangrilá, and stable to slightly prograding to the south, although a recent trend of erosion has been registered south of Tramandaí. It is interesting to note that the short-term changes reflect differences in the behavior of modern transgressive dune fields, and that the estimated medium-term rates of change agreed well with the long-term trend observed during the Holocene.

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CAPÍTULO 5

SEASONAL AND INTERANNUAL INFLUENCES ON THE PATTERNS OF SHORELINE CHANGES IN RIO GRANDE DO SUL, SOUTHERN BRAZIL

Esteves, L.S.; Williams, J.J. & Dillenburg, S.R. 2004. Seasonal and interannual influences on the patterns of shoreline changes in Rio Grande do Sul, southern Brazil. *Journal of Coastal Research*, submetido.

ABSTRACT

This paper analyses changes in shoreline positions along the coast of the Rio Grande do Sul, southern Brazil, to determine the alongshore variability of seasonal and interannual patterns of shoreline change at a regional scale. Shoreline position data were obtained by kinematic DGPS applied to map the 618-km long coastline five times between November 1997 and April 2002. The data show that the shoreline responds differently to seasonal and interannual variations along the three major coastal sectors, especially in the magnitude of changes, in the time-interval in which the shoreline returns to a previous position, and in the dominant length-scales over which the shoreline changes occur. Spatial and temporal changes in shoreline position are examined with respect to the influences of grain size, shoreline orientation, longshore sediment transport, storms, and ENSO events. Present results indicate that the alongshore variability in the patterns of change is strongly influenced by changes in shoreline orientation and the associated effects on gradients of longshore transport. Variations in wave energy and storminess determine the seasonal patterns of shoreline changes while ENSO events are likely to influence the registered interannual changes. It was observed that the short-time scales for the shoreline to return to a previous shape and position varied for different beach segments. This raises the question whether such shoreline shapes and positions are dominant through time or merely represent transitory moments between dynamic states. These results demonstrate the importance of regional studies to improve understanding of the factors driving both temporal and spatial variability of shoreline changes.

Additional Index Words: beach erosion, DGPS, storms, El Niño, longshore sediment transport

INTRODUCTION

Frequently, sandy coastlines exhibit alongshore variability at a wide range of spatial and temporal scales. Coastal changes are a result of processes acting on the scale of few millimeters and seconds (at sand grain levels) up to scales of hundreds of kilometers and centuries (regional sand budget) in a way that variations observed at any scale affect the others (KOMAR, 1999). Coastal processes interact with each other producing complex patterns of shoreline changes where alternating areas of net erosion and accretion found adjacent to one another at one time may exhibit opposite trends at another time. Understanding beach response to variations in wave energy conditions, tides, storminess, *etc*. at different time-scales is a minimum requirement for coastal engineering projects and management practices (DOUGLAS *et al.*, 1998; HONEYCUTT *et al.*, 2001; PAJAK and LEATHERMAN, 2002). This is especially important at a regional scale, where coastal management decisions are taken and better scientific knowledge is required (STOCKDON *et al.*, 2002). The main problem associated with sustainable development of the coastline is attributable to short-term extreme events. Thus, for many practical applications, it is essential to develop accurate techniques to determine the maximum amplitude of the waterline fluctuations and the frequency of their occurrence.

Very few studies in Rio Grande do Sul (RS) and in Brazil have addressed contemporary coastal processes or beach changes at a regional scale. Most have been limited to discontinuous monitoring of beach profiles in few places (ESTEVES *et al.* 2003a). Aerial photos are also scarce, usually limited to recent years, covering short coastal segments, and often of inadequate scale. Only recently the use of kinematic Global Positioning System (GPS) method allowed collection of shoreline position data continuously along the RS (TOLDO *et al.*, 1999; ESTEVES *et al.*, 2003a). Additionally, the lack of wave measurements along the RS makes difficult to determine the local wave climate or estimate any parameters based on wave conditions. In the present study, a data set of shoreline positions obtained by kinematic GPS along the 618 km of the RS coastline is analyzed. Shoreline mapping was conducted five times from 1997 to 2002 and the seasonal, interannual, and spatial variability in the observed shoreline changes are quantified in this paper at a regional scale. Additionally, the influence of the following factors is examined: sediment grain size, shoreline orientation, wave climate, storms, the El Niño-Southern Oscillation (ENSO), and the net longshore sediment transport rates. Results presented here improve understanding of relationships between the principal forcing conditions that affect the morphology of a coastline which have a broad application at other sites worldwide.

STUDY AREA

The study examines the 618-km long shoreline of RS, Brazil, which extends from the Brazil-Uruguay border in the south to the Santa Catarina state border in the north. This coastline has an approximately NE-SW orientation and an undulated shape due to the presence of two large-scale projections and two embayments (Figure 5.1). Three major coastal sectors can be identified: (a) the southern sector, extending 220 km from the Chuí creek at the Uruguayan border to the Patos Lagoon inlet, is one of the longest continuous sandy beaches in the world; (b) the undeveloped central sector, extending about 275 km north from the Patos Lagoon inlet, is bisected only by the intermittent opening of the Peixe Lagoon entrance; and (c) the highly urbanized northern sector, extending a further 123 km to Torres, is bisected by the Tramandaí Lagoon inlet (Figure 5.1).

The RS shore is part of a large coastal plain formed and shaped by the Quaternary sea-level fluctuations that resulted in a complex system of coastal lakes and lagoons. Most of the fluvial sediment inputs are retained in the lagoon system, restricting the sand supply from inland to the shore (TOMAZELLI *et al.*, 1998). As such conditions have existed since the regression following the maximum of the Holocene transgression (the last 5 ka), alongshore gradients of wave energy might have controlled the coastal sediment budget due to concentration of wave rays in large-scale coastal projections and dissipation in the embayments (DILLENBURG *et al.*, 2000). Tidal variation is less than 0.5 m along the RS coast (TOMAZELLI *et al.*, 1998). Waves are the main hydrodynamic agent with mean significant height (H_s) of 1.4 m and peak period (T_p) of 7 s to 9 s that can exceed 3 m and 12 s, respectively during the passage of extratropical cyclones (ALMEIDA and TOLDO, 1997).

Wind and wave conditions along the RS coast are determined by two high-pressure systems: (1) the Atlantic anticyclone that is semi-fixed with center around 30°S over the southern Atlantic Ocean, and (2) the mobile Polar anticyclones (KRUSCHE *et al.*, 2002; SARAIVA *et al.*, 2003). The first generates tropical maritime air masses of high temperature and humidity,

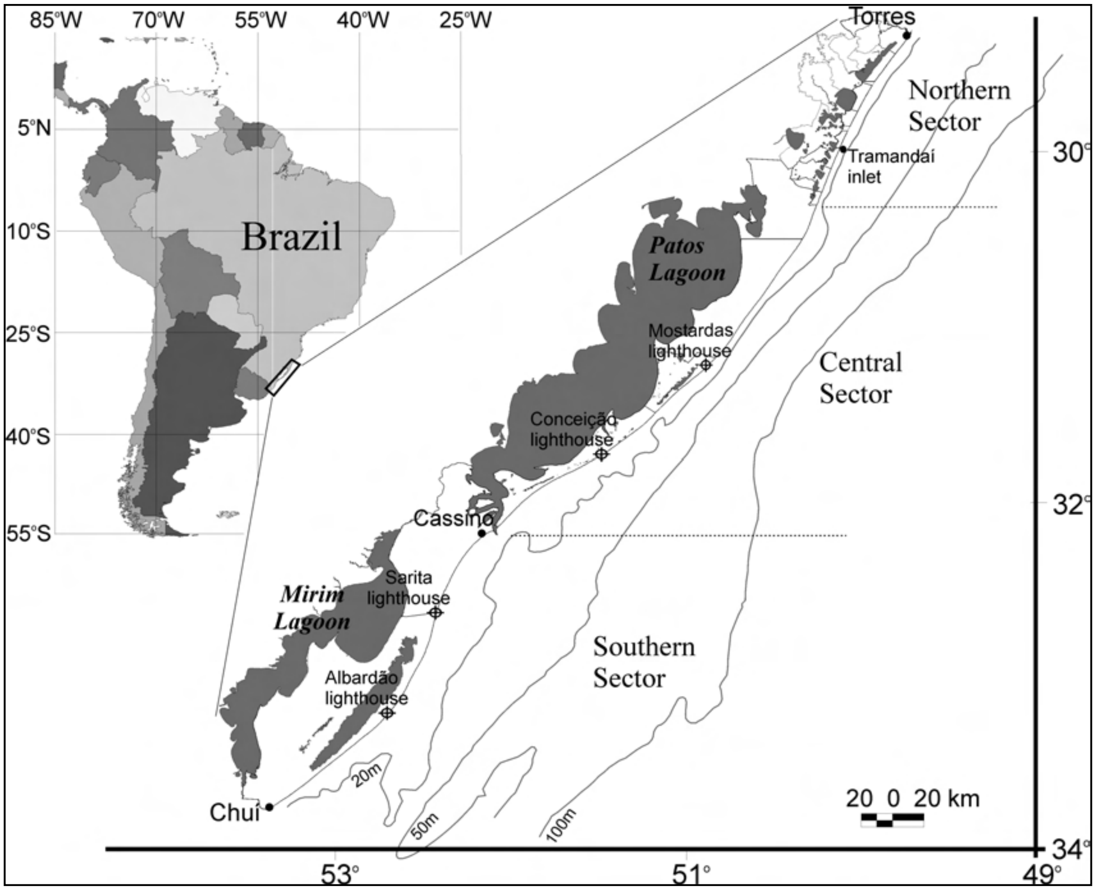

Figure 5.1. The study area showing: the 620-km long shoreline of Rio Grande do Sul, and three major coastal sectors: (a) southern, (b) central, and (c) northern. Note the approximately NE-SW orientation and undulated shape of this shoreline due to the presence of two large-scale projections and two embayments. Gray lines are bathymetric contours of 20 m, 50 m, and 100 m.

responsible for the NE winds that dominate along the RS shore most of the year (SARAIVA *et al.*, 2003). The polar anticyclones migrate to lower latitudes as stable, cold, and dry air masses generating winds from S, SW, and SE. The Atlantic anticyclone weakens and moves to lower latitudes in the winter, allowing the polar anticyclones to reach further north, resulting in stronger and more frequent southerly winds from April to July.

Whilst observed longshore currents are bi-directional (NICOLODI *et al.*, 2000), coastal geomorphic features indicate a net northward sediment transport (TOMAZELLI and VILLWOCK, 1992) driven by larger waves from the south. Such waves are associated with the passage of frontal systems that reach the RS coast on average four times per month (SARAIVA *et al.*, 2003), increasing to 6-7 per month in the winter (OLIVEIRA, 1986). The passage of cold fronts also generate strong SW winds (*e.g.* BRAGA and KRUSCHE, 2000) which often result in storm surges $O(1\ \mathrm{m})$. These are more frequent in the fall and occur along the RS beaches in two situations: (1) a low-pressure system over the ocean is intensified by the presence of a high-pressure system over the continent creating a long fetch for a cyclone migrating from SW thereby piling water onto the shore due to the Ekman transport, and (2) a cyclone is formed over the continent (in RS, Uruguay, or Argentina) and moves towards the shore generating strong local winds and high waves (SARAIVA *et al.*, 2003).

Intermediate beaches composed by well-sorted fine quartzose sands dominate in the RS (*e.g.* TOLDO *et al.*, 1993; CALLIARI and KLEIN, 1993; BARLETTA, 2000), except along (a) a 30-km long segment between Albardão lighthouse and Hermenegildo (in the southern sector) where reflective to intermediate beaches are composed by bimodal sediment due to the addition of bioclastic gravels, and (b) the dissipative beaches from Cassino Beach to Sarita Lighthouse (southern sector), where the suspended sediments carried through the Patos Lagoon mouth decrease the mean grain size along Cassino Beach (CALLIARI and KLEIN, 1993). The average beach slope is 1/30 along the northern coastal sector (TOLDO and ALMEIDA, 2003), varying from 1/26 to 1/40 along the central sector (BARLETTA, 2000), and from 1/13 to 1/30 along the southern sector (CALLIARI and KLEIN, 1993).

METHODS

This study compares shoreline positions mapped in 1997 (November 26th-28th), 1998 (November 17th-19th), 1999 (November 10th-11th and 19th), 2000 (June 26th-28th), and 2002 (April 15th-17th) to determine alongshore patterns of shoreline changes at a regional scale. Hereafter, for convenience, these surveys are referred to as Nov1997, Nov1998, Nov1999, Jun2000 and Apr2002, respectively. Using the swash line as the reference feature, the shoreline was mapped by the kinematic GPS method (*e.g.* MORTON *et al.*, 1993; TOLDO *et al.*, 1999). Three days and

U$1,000 were required to complete the 618-km long survey, making the kinematic GPS a fast and economic method to monitor the state's shoreline. In 1997, two Garmin GPS 100 Personal Surveyor were used; one installed in a vehicle moving along the swash line at an average velocity of 50 km/h registering positions every 5s, and the other was set in static mode every 100 km. The horizontal precision of the shoreline position was 3 m after data correction. In the following years, data corrections were based on a fixed GPS antenna, and in 2000 and 2002, a Trimble GPS 4600 was used to map the shoreline, improving the horizontal accuracy in shoreline positions to 1 m.

Although previous surveys were referenced to the swash line, the high water line (HWL) was the feature mapped in 2002. Therefore a correction factor was applied to allow comparison with the other lines. The correction was based on the mean values of the distances between the HWL and the swash line measured every 200 m to 500 m on aerial photos taken in 1989 and 2000. The mean values were determined for segments presenting similar characteristics and used as a correction factor to displace the shoreline mapped in 2002 seawards. The swash line and the HWL are easily identified while driving along the beach (*e.g.* PAJAK and LEATHERMAN, 2002) and were used to map the shoreline because they are the only reference features that can be followed continuously throughout the length of the study area. TOLDO and ALMEIDA (2003) consider that the errors in mapping the RS shoreline using the swash line as reference feature are attributable to the gentle slope of the beaches, tidal variation, storm surges, and wave run up. To reduce some of these errors, shorelines were mapped when tide and meteorological conditions were similar. The difference in tidal levels during the surveys was < 0.2 m, and no storms or passage of cold fronts were registered in the weeks before fieldwork. Measurements of waves along the RS coast for the period of the GPS surveys are not available. However, considering a wave run up of 0.55 m estimated for RS beaches (TOLDO and ALMEIDA, 2003), a tidal variation of 0.2 m, and no storm surges, the potential errors on the horizontal position of the mapped shorelines are estimated for different beach segments according to their slope. Along the northern coastal sector, beach slope is usually 1/30, resulting in a horizontal error of 22.5 m or around ±11 m (6 m due to tidal variation and 16.5 m due to run up). Along the central sector, beach slope varies from 1/26 to 1/40, resulting in a horizontal error ranging from 19.5 m (about ±10 m) to 30 m (±15 m), respectively. The beach slope along the southern sector varies from 1/13 to 1/30, so the estimated potential horizontal errors range from 9.75 m (about ±5 m) to 22.5 m (around ±11 m), respectively. Vertical bars representing the cumulative error for different sectors of the coast are displayed in the shoreline change graphs only for selected points to avoid interfere in the clarity of the figure. The errors estimated for the horizontal position of the waterline are very similar to the mean values of the distances measured between the HWL and the swash line, indicating that they provide a consistent correction factor between those reference features.

Mapped shorelines were displayed and organized in ArcView GIS 3.2. The ArcView extension *Digital Shoreline Analysis System 2.0* (DSAS 2.0), developed by the U.S. Geological Survey (THIELER *et al.*, 2003), was used to measure changes in shoreline position and rates of change every 250 m alongshore. Graphs of alongshore distance *vs.* shoreline changes or rates of change use the following convention: landward movements (shore retreat) are given negative values, seaward movements (beach accretion) are given positive values, and alongshore distance was measured from south to north, starting at the jetty of the Chuí creek. Although the GPS data provides detailed snapshots of the shoreline positions useful for examining alongshore differences and interannual and seasonal changes, it cannot be used to deduce long-term trends. Such trends in shoreline movements can only be observed after decades of continued monitoring and are therefore not considered further here.

Central to studies of all sandy coastlines is a requirement for accurate predictions of the longshore sediment transport (LST) rate. Most formulae state that the LST is proportional to the longshore wave energy. Here LST is calculated using the CERC formula (USACE, 1984) in the form

$$Q = \frac{K}{16(s-1)(1-p)}\sqrt{\frac{g}{\xi}}H_{s,b}^{2.5}\,sin(2\theta_b)$$

where Q is the volumetric sediment transport rate expressed in units of m^3s^{-1}, K is the so-called CERC constant, s is the specific density of the sediment, $\underline{p}$ is the sediment porosity, ξ is a wave breaker index, often taken to be 0.78 (WEGGEL, 1972), $H_{s,b}$ is the wave breaker height and θ_b is the wave breaker angle relative to the shoreline. In the present study, methods used to obtain $H_{s,b}$ and θ_b values using deep water wave scenarios described below assume straight regular contours and follow linear wave theory. Further details are given by WILLIAMS *et al.* (in preparation). Here we use $p = 0.32$, a well accepted value for fine and medium sand. It is noted that several parameters that logically might influence LST are apparently excluded explicitly from the CERC formula, including the breaker type, the beach slope, and the sediment grain size. These are generally considered to be encompassed by the $\underline{K}$ parameter. BAILARD (1981) reports that in conditions where 2.5 cm/s < w_s < 20.5 cm/s, $0.2^o < \theta < 15^o$ and 0.3 m/s < $u_{w,b}$ < 2.83 m/s:

$$K = \int \theta, u_{w,b}/w_s = 0.05 + 2.6\,sin^2(2\theta) + 0.007(u_{w,b}/w_s)$$

where $u_{w,b}$ is the RMS wave orbital velocity at the breaker point and w_s is the sediment settling velocity defined by SOULSBY (1997) as

$$w_s = \frac{\nu}{D_{50}}\left[\left(10.36^2 + 1.049 D_*^3\right)^{0.5} - 10.36\right]$$

where ν is the kinematic viscosity of water. Here we choose to use K values from the Bailard equation as they account for hydrodynamic and sediment properties and the equation is valid for conditions pertaining along the RS shoreline.

ALONGSHORE VARIABILITY IN THE SEASONAL AND INTERANNUAL PATTERNS OF SHORELINE MOVEMENTS

The present GPS data allows study of shoreline changes continuously along RS at various spatial scales. At a regional scale, *i.e.* along the three major coastal sectors, seasonal and interannual variations in the shoreline position exhibit different responses either in the magnitude of displacements and/or in the time-scale in which the shoreline returns to a previous position (ESTEVES *et al.*, 2003a). Analysis of data pertaining to shoreline positions along RS allows identification of the general differences in the patterns of shoreline movements presented and discussed below.

Annual changes in the shoreline position are represented here by the displacements registered between lines mapped in Nov1997, Nov1998, and Nov1999 (Figure 5.2a). Patterns of annual shoreline movements are significantly different along the three major coastal sectors: seaward movements (*i.e.* accretion) are observed along most of the southern sector, a rhythmic pattern of alternating shoreward and landward movements occurs along the central sector, and a less pronounced rhythmic pattern occurs along the northern sector showing accretion from Nov1997 to Nov1998 and erosion from Nov1998 to Nov1999 (Figure 5.2a). Larger magnitudes of changes (almost 150 m) occur along the central sector, and lower magnitudes along the northern and southern sectors, where they are mainly within the 50 m range.

Morphodynamic studies indicate that beach profiles tend to show accretion in the summer (December to March) as a result of the dominant fair weather conditions, and erosion in the winter (June to August) due to the more energetic conditions (*e.g.* BARLETTA, 2000; WESCHENFELDER *et al.*, 1997; CALLIARI and KLEIN, 1993). This seasonal behavior is observed in figure 5.2b, showing landward movements of the shoreline dominating from Nov1999 to Jun2000 and seaward movements dominating from Jun2000 to Apr2002. The Nov1999-Jun2000 line represents the erosion that prevails in the fall-winter months as it compares an accreted shoreline mapped at the end of spring (November) with an eroded shoreline mapped in the winter (June). Conversely, the Jun2000-Apr2002 line shows accretion

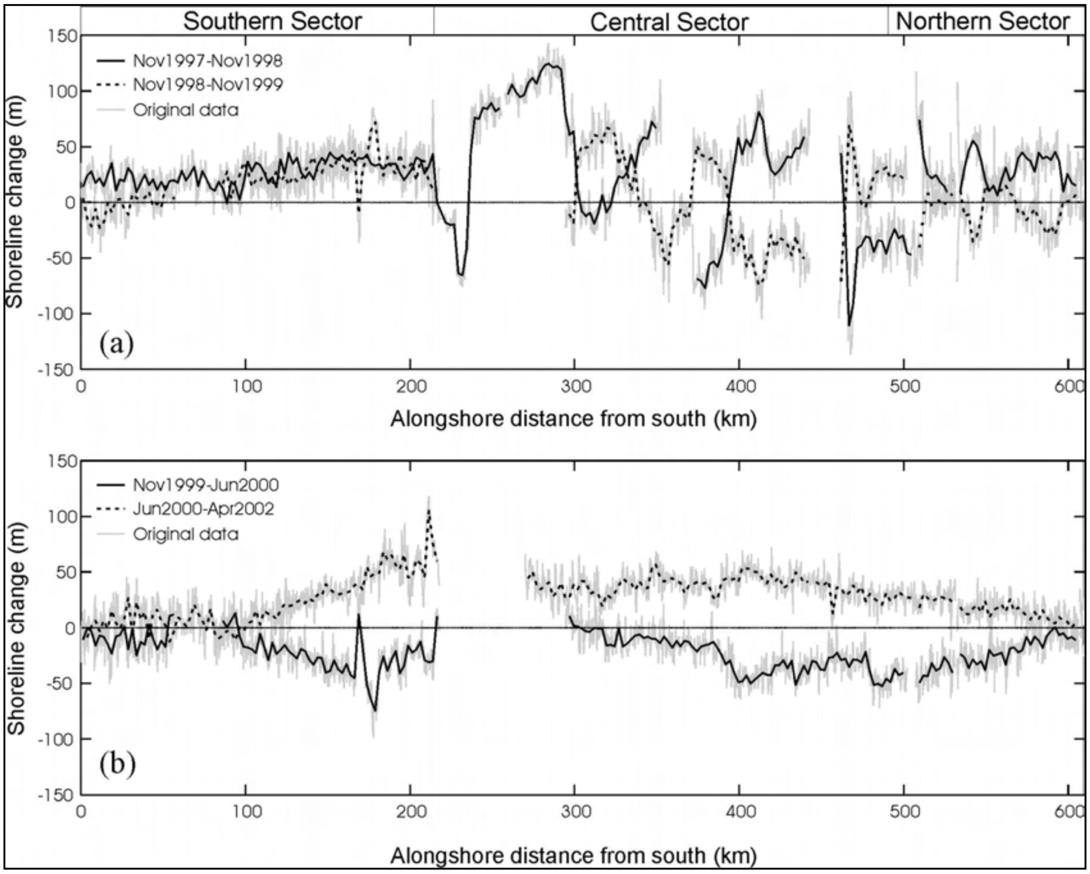

Figure 5.2. Shoreline change graphs for the RS coast, showing annual (a) and seasonal (b) changes in the shoreline position (original data is shown in gray and moving average lines in black). Annual changes are represented by the displacements in the shoreline positions registered from Nov1997 to Nov1998 and from Nov1998 to Nov1999. Seasonal changes are represented by shoreline movements registered between Nov1999 (spring) and Jun2000 (winter), and between Jun2000 and Apr2002 (beginning of fall). Note that seaward movements of the shoreline (accretion) are identified by positive values and landward movements (erosion) by negative values.

due to the calm conditions of the spring-summer months as it compares a shoreline mapped in winter with a shoreline mapped in April, before the first storms of fall.

The alongshore variability is observed also in the length-scales over which the shoreline changes occur in RS. Here wavelet analysis (TORRENCE and COMPO, 1998) using a Morlet wavelet was used to assist in the identification and quantification of the dominant length-scales of change in the RS shoreline position. Wavelet analysis has the advantage of representing the frequency spectrum in a two-dimensional plot, and shows the spatial variability in the dominant length-scales along the shore. Results of the wavelet analyses for the entire RS shoreline are shown in Figure 5.3. Figure 5.3a shows annual changes between November 1997 and November 1998 and Figure 5.3b shows seasonal changes between June 2000 and April 2002. This figure also includes plots of the shoreline position data used in the analyses. Gaps in the data series are

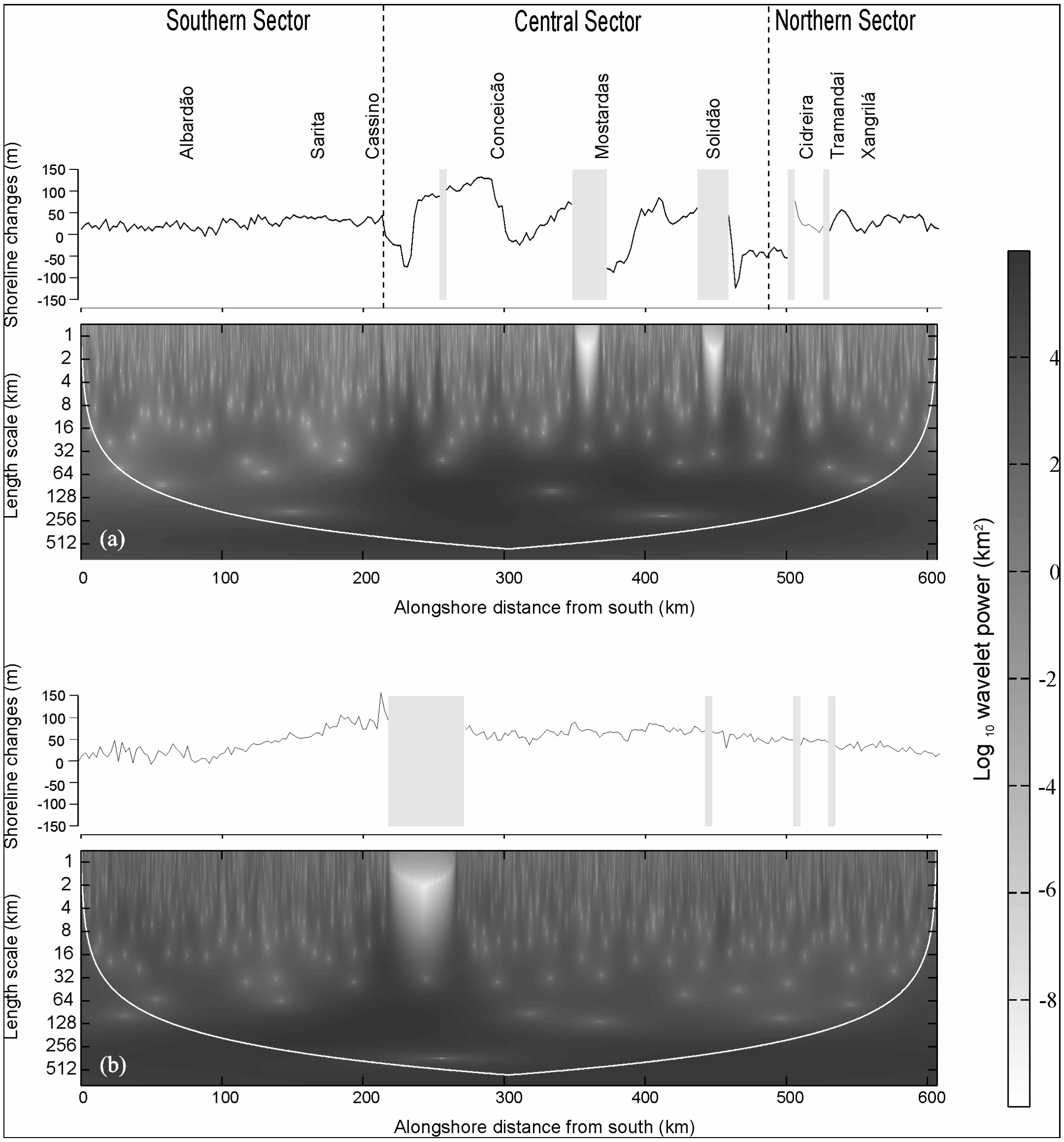

Figure 5.3. Results from wavelet analysis of shoreline change data used to identify the dominant length-scales over which the majority of shoreline changes occur. The wavelet spectra (a) for the period Nov1997 to Nov1998 represents annual changes and show that variations in the shoreline changes in the southern, central and northern sectors occurs dominantly at length scales *O*(10 km), *O*(100 km), *O*(30 km), respectively. The wavelet spectra (b) for the period Jun2000 to April2002 represents seasonal variations and does not show a strong concentration of energy at any particular length-scale and evidences that variations in shoreline position occur at length scales *O*(10 km) along the whole shoreline. The solid white line on the figure indicates the maximum resolvable length scale. Plots of the shoreline changes used in the analyses are presented on top of the respective wavelet spectra.

indicated by the gray shading. The results in Figure 5.3a show that the majority of shoreline variation occurs at length scales *O*(10 km) *O*(100 km) *O*(30 km) in the southern, central and northern sectors, respectively. Whilst wavelet analysis of the seasonal shoreline displacements does not show a strong concentration of energy at any particular length-scale (Figure 5.3b), it is evident that seasonal variations in shoreline position occur at much shorter length scales *O*(10 km) along the whole shoreline. These results indicate that the alongshore variability in the annual changes along the central and northern sectors are due mainly to low-frequency changes in shoreline position, which appear to be related to the rhythmic pattern observed in those sectors (Figure 5.2a). Such pattern was not observed in the annual or in the seasonal changes along the southern sector, where high-frequency variations are more important in determining the alongshore variability of both annual and seasonal shoreline changes. The wavelet analysis reveals therefore that despite the apparent uniformity of the coastline, quite different coastline responses are observed to both the evolution time and the geographical location. It is noted also that in the case of the annual changes (Figure 5.3a), the dominant length scales of change are different along each of the two major coastal projections and along each of the two major embayments. Other data series analyzed using wavelets exhibited similar properties (not illustrated).

Southern Sector

From Nov1997 to Nov1998, beach accretion dominates along the southern sector except in a 15-km long segment 85 km north of Chuí, where peaks of erosion occur in the area of the Albardão Lighthouse (Figure 5.4a). The mean shoreline change is 25.9 m with standard deviation of 13.9 m, and peaks of accretion and erosion reaching 91.6 m and –18.1 m, respectively (Table 5.1). South of Albardão, magnitudes of seaward movements are mainly within the 0 m to 40 m range, and increase to 20 m to 60 m northwards. Seaward movements also dominate from Nov1998 to Nov1999, except along the southernmost 50 km (Figure 5.4a). The presence of erosion areas in this line results in a lower mean shoreline change (19.1 m) and a larger standard deviation (21.3 m) than in the previous year (Table 5.1).

A seasonal effect is evident along the northern part of the southern sector when shoreline displacements represented in the Nov1998-Nov1999 and Nov1999-Jun2000 lines are compared (Figure 5.4b). In that segment, the accretion observed in one year (Nov1998 to Nov1999) is matched by retreat in the following winter, with an interval of seven months. Peaks of maximum accretion and erosion have similar magnitudes and are spatially coincident producing an almost perfect mirror image (mean line around zero). The mirror effect indicates the return of the shoreline to a pre-existing position, suggesting that the shoreline has a "memory" of its original shape (LIST and FARRIS, 1999). The opposite behavior of the Nov1998-Nov1999 and Nov1999-Jun2000 lines is evidenced by the mean shoreline change values of similar magnitude and opposite signs (Table 5.1) and by the high negative correlation factor (-0.75). A mirror image

Table 5.1. Shoreline Change Statistics by Coastal Segments and Time Interval, Rio Grande do Sul, Brazil.

		1997-1998	1998-1999	1999-2000	2000-2002
Mean (m)	South	25.9	19.1	-19.6	21.6
	Central	27.3	0.3	-24.1	37.9
	North	21.6	-2.5	-24.4	17.4
Standard Deviation (m)	South	13.9	21.3	19.5	25.8
	Central	60.2	42.4	18.6	11.7
	North	29.8	22.5	16.3	11.7
Minimum (m)	South	-18.1	-44.8	-98.8	-33.4
	Central	-136.3	-104.7	-71.6	-0.9
	North	-75.1	-68.3	-67.7	-13.1
Maximum (m)	South	91.6	85.0	32.2	117.5
	Central	142.6	99.3	25.9	71.8
	North	117.2	107.7	18.9	44.1

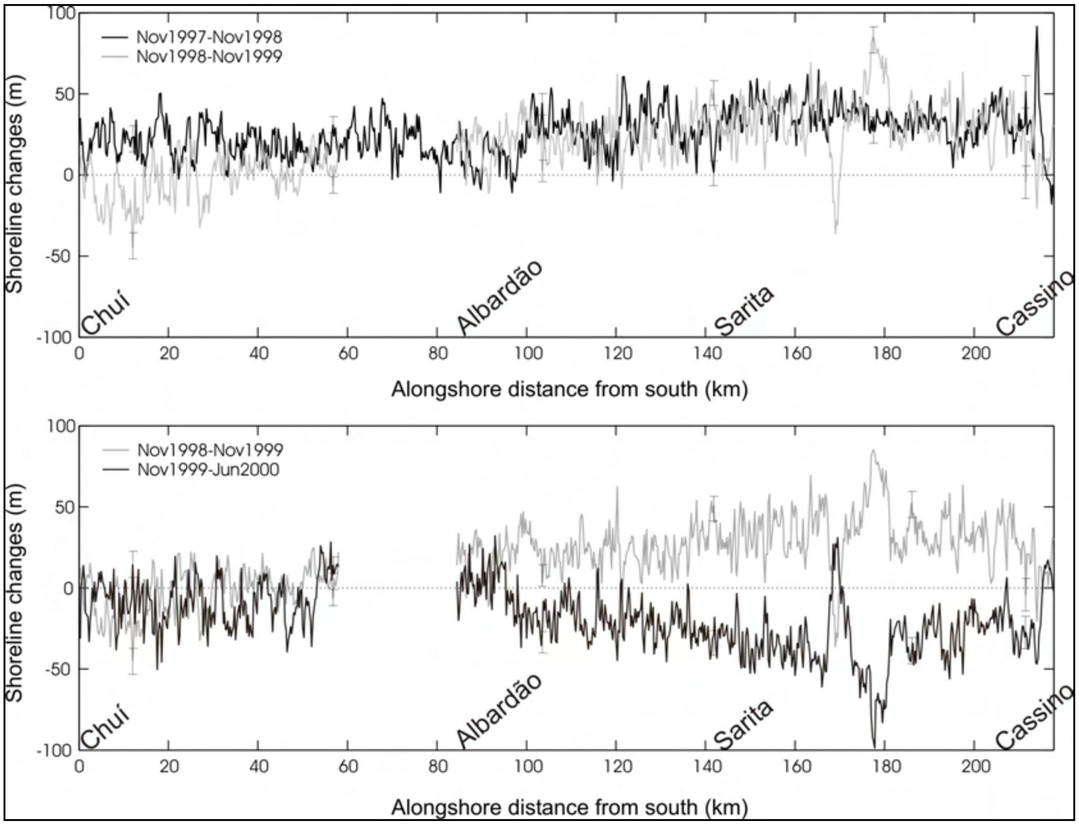

Figure 5.4. Shoreline changes along the southern coastal sector. Annual changes (a) are represented by shoreline movements registered from Nov1997 to Nov1998 and from Nov1998 to Nov1999. Seasonal changes (b) are determined by comparison of shoreline movements registered between the Nov1998 to Nov 1999 and Nov1999 (spring) to Jun2000 (winter) intervals. Vertical bars represent the estimated error in the horizontal shoreline position. *Seaward movements of the shoreline are identified by positive values and landward movements by negative values.*

is not observed along the southernmost segment at the same time-scale. However, shoreline changes of similar magnitude and opposite direction (although not showing the same exact shape or coincident peaks) occur along the southernmost 30 km when comparing the Nov1997-Nov1998 and Nov1998-Jun2000 lines.

As observed before, the southern sector can be divided into two segments defined by differences in the short-term shoreline changes. These segments also show a different trend in the long-term (the last 5 ka), as the area north of Albardão has been prograding and the southern area has been retreating (DILLENBURG *et al.*, 2000). In the southernmost 90 km, accretion in one year is followed by erosion in the next, and alternate areas of erosion and accretion occur alongshore at scales of 4 km to 6 km. Similar alongshore variability at a scale of 5 km to 10 km was reported for the coastlines of the Outer Banks (North Carolina, USA) and Cape Cod (Massachusetts, USA) by LIST *et al.* (2003). The northernmost 130 km is characterized by larger magnitudes of changes with accretion in November (annual lines) being approximately balanced by erosion in the following winter (Figure 5.4b). As accretion was registered in both annual lines (Figure 5.4a), this raises the question whether such accretion is always balanced by erosion in the following winter, resulting in a state of quasi-equilibrium in the short-term. Considering that the long-term trend is still valid, it is likely that a net accretion exists in the medium (decades) to long-term (centuries to millennia) even if there is a short-term (seasonal) balance between erosion-accretion. The mean shoreline change for the northern 130 km is 29.5 m from Nov1998 to Nov1999 and -27.4 m from Nov1999 to Jun2000, indicating a positive net balance in the short-term that might be contributing to the long-term progradation. Although there is evidence that this area is accreting in the short and medium terms, rates of accretion have decreased in time as shown by comparison of aerial photographs from 1947, 1974, and 2000 (LÉLIS and CALLIARI, 2003).

Central Sector

Annual changes along the central sector are characterized by oscillatory movements, with alternating adjacent areas of erosion and accretion (Figure 5.5) occurring at scales $O(30$ to $100)$ km. This is evident in the results from the wavelet (Figure 5.3a). It is interesting to note that in consecutive years, the shoreline movements are in opposite directions, *i.e.* areas that have eroded from Nov1997 to Nov1998 have accreted in the following year and *vice-versa*. Peaks of maximum changes are spatially coincident but show different magnitudes, resulting in a mean line that fluctuates around zero at Mostardas (from 370 km to 400 km north of Chuí) and exhibits a net seaward movement to the south and a net landward displacement to the north. Magnitudes of changes and alongshore variability are greater along the central sector for both years, although

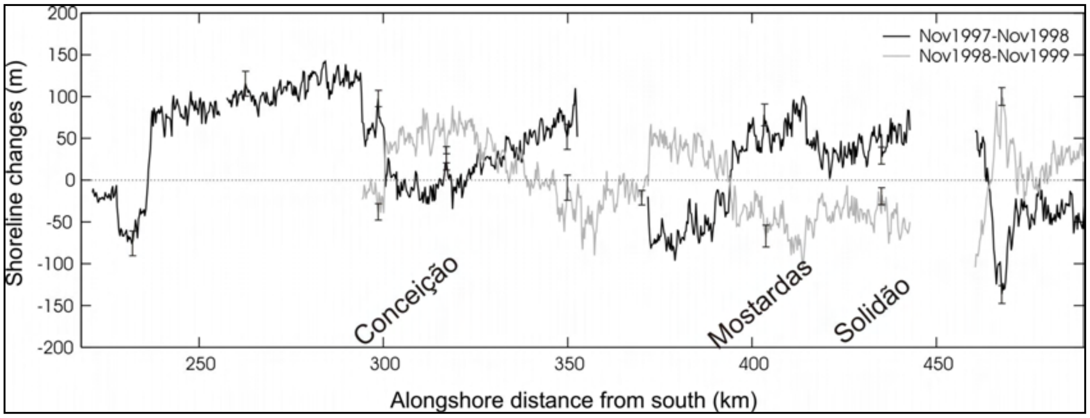

Figure 5.5. Annual changes in the shoreline position along the central sector from Nov1997 to Nov1998 and from Nov1998 to Nov1999. The estimated cumulative error in the horizontal shoreline position is represented by vertical bars. *Note that seaward movements of the shoreline are identified by positive values and landward movements by negative values*.

variations are larger in the Nov1997 to Nov1998 period, as reflected by the standard deviation and maximum and minimum values shown in Table 5.1.

The oscillating pattern observed in the annual shoreline change lines (Figure 5.5) is not present in the Nov1999-Jun2000 and Jun2000-Apr2002 lines (Figure 5.2b). This observation indicates that a rhythmic shoreline configuration is a temporary or seasonal feature. Magnitudes of displacements increase from south to north and are dominantly landward from Nov1999 to Jun2000 with a mean value of -24.1 m (Table 5.1). In contrast, seaward movements dominate from Jun2000 to Apr2002 with a mean value of 37.9 m. As discussed above, these lines reflect seasonal changes, *i.e.* the erosion due to the high-energy conditions in fall-winter and the beach recovery in the summer. Magnitudes and the alongshore variability of shoreline changes are considerably lower in these lines than in the annual lines, as can be observed in the lower values of maximum, minimum, and standard deviation of shoreline displacements (Table 5.1). High-frequency changes are not very import in any of the displacement lines, as most of the energy of the spectra is concentrated in variations of longer scales, as demonstrated by the wavelet analysis (Figure 5.3).

Northern Sector

Along the northern sector, annual displacement lines show an undulating shape and are opposed to each other (Figure 5.6a). The dominant shoreline movement was seaward from Nov1997 to Nov1998 with a mean value of 21.6 m (Table 5.1). Although erosion dominated from Nov1998 to Nov1999 (mean of –2.54 m), the displacement line oscillates around zero alternating areas of accretion and erosion in some beach segments (Figure 5.6a). In common with the other sectors, magnitudes of change are larger for the Nov1997-Nov1998 line. Figure 5.6a shows also that areas where magnitudes of shoreline changes are greater (generally 40 m to 60 m) are about three times longer than the adjacent areas where changes are minor (from 0 m to 20m).

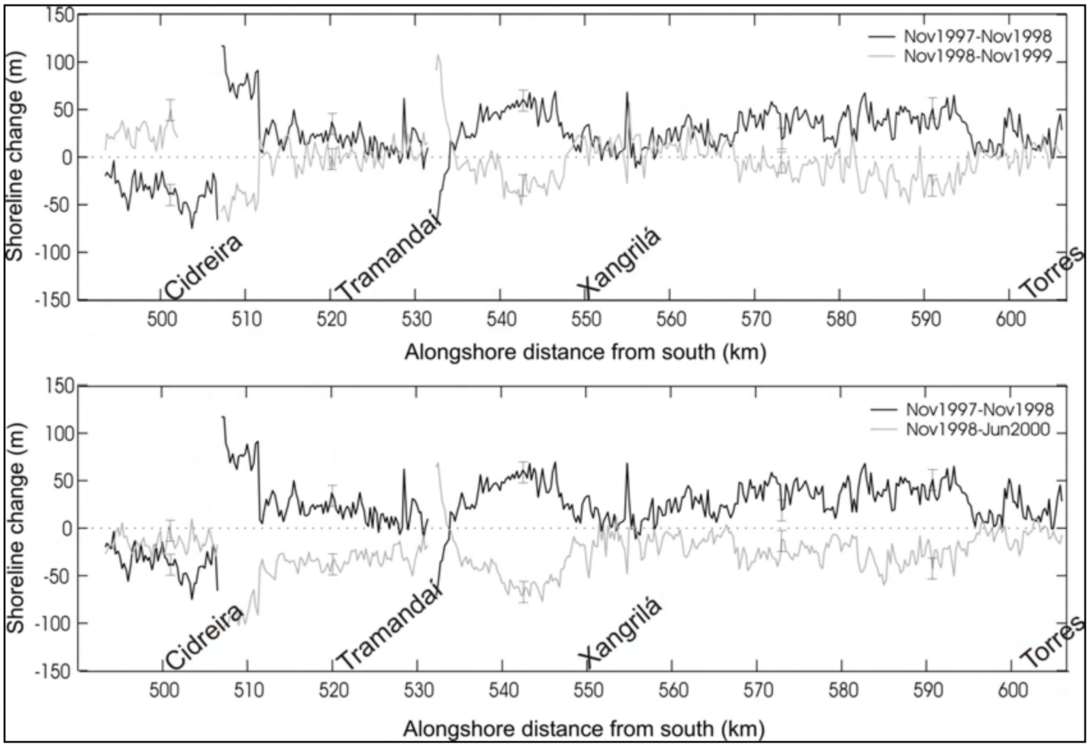

Figure 5.6. Shoreline changes along the northern sector, showing the undulating shape of the annual displacements lines (a), where shoreline movements were dominantly seaward from Nov1997 to Nov1998 and dominantly landward from Nov1998 to Nov1999. Observe that the accretion registered from Nov1997 to Nov1998 is balanced by erosion from Nov1998 to Jun2000, forming an approximate mirror image (b). Vertical bars represent the cumulative error in the horizontal shoreline position.

The seasonal lines Nov1999-Jun2000 and Jun2000-Apr2002 show mainly erosion and accretion, respectively, with magnitudes of changes decreasing from south to north (Figure 5.2b). Similarly to the southern sector, an approximate mirror image is observed along the northern sector but at a longer time-scale (Figure 5.6b). The accretion registered from Nov1997 to Nov1998 is balanced by erosion in the Nov1998 to Jun2000 interval, *i.e.* 19 months later. A mean line derived from the Nov1997-Nov1998 and Nov1998-Jun2000 lines shows a recovery of the previous shoreline position from the Tramandaí inlet to Xangrilá, with a slightly negative balance southwards of this area and a positive balance northwards. A shoreline change analysis based on aerial photos from 1974, 1989, and 2000 also indicates that beaches have been stable from Tramandaí to Xangrilá (ESTEVES *et al.*, 2004). In the long-term, the barrier has prograded from Torres to Tramandaí and has been stable to the south (DILLENBURG *et al.*, 2000). So it seems that the area from Tramandaí to Xangrilá marks a transition between areas that are accreting in the short and long-terms (to the north) and areas that have been stable in the long-term and eroding in the medium to short-term (to the south). North of Xangrilá, transgressive dunes are limited to a narrow fringe (100 m to 500 m) projecting from the modern foredunes, while the Holocene barrier is completely covered by transgressive dunes to the south (DILLENBURG *et al.*, 2000) indicating shoreline retreat. Determining if this represents a change in the long-term trend for the beaches south of Tramandaí or if it simply indicates a transient moment in a highly variable short-term fluctuation requires further monitoring of shoreline position.

THE INFLUENCE OF PATTERNS OF SHORELINE MOVEMENTS ON THE RATES OF CHANGE

Earlier studies have emphasized that mapped shorelines might not represent a mean seasonal position, especially when they are influenced by large short-term changes (*e.g.* DOLAN *et al.*, 1980; SMITH and ZARILLO, 1990). However, given that the mean shoreline position is not necessarily dominant in time, it is considered here that is more important to consider which is the modal (*i.e.* more frequent) shoreline position and shape at different time-scales (SMITH and ZARILLO, 1990). Additionally, as a great part of the hazard to coastal development is attributable to short-term extreme events, for management purposes it is essential to estimate the maximum changes of the waterline and how frequently they occur.

A long-time record of shoreline positions is required to estimate rates of changes. Thus, the available data do not provide information sufficient to derive a reliable estimation of the long-term rates for the RS coast. However, graphs showing short-term rates of change are presented to illustrate the effects of the patterns of shoreline displacements on the magnitude and trends of shoreline change rates. Here, rates of shoreline change were estimated by the linear regression and end-point methods using different time intervals (1997 to 2002 and 1998 to 2002).

Rates estimated by the linear regression and end-point methods show similar trends along most of the RS coastline, although differences in the magnitudes of rates are observed in areas of high mobility such as the central sector (Figure 5.7a). Rates of changes estimated by the end-point method for the periods 1997 to 2002 and 1998 to 2002 are similar along the southern sector and show different magnitudes and trends along the central and northern sectors (Figure 5.7b). The similarity and lower magnitudes of the annual displacements observed along the southern sector result in rates of similar magnitudes and trends independently of the shoreline position data used. On the other hand, the oscillatory and reversed behavior of the shoreline movements along the northern and central sectors produces rates of changes with magnitudes and trends that are considerably different depending on which shorelines are compared (ESTEVES *et* *al.*, 2003b). Rates estimated by the linear regression method for 1997 to 2002 and 1998 to 2002 also show differences in the magnitudes of rates, but trends differ only along parts of the central sector, where annual changes to opposite directions are more pronounced.

Several studies have shown that shoreline change rates estimated by linear regression are more reliable than the ones obtained by the end-point method, mainly because the second uses only two data points and is extremely dependent on the conditions they represent (*e.g.* CROWELL *et al.*, 1997; HONEYCUTT *et al.*, 2001; FENSTER *et al.*, 2001). The results obtained for the RS coastline show that the linear regression method can be used to assess the trends of short-term rates, except for the areas where magnitudes of annual displacements are large (> 60 m) and occur to opposite directions. At the same time, it is clear that rates based on only two data points can differ enormously, even showing opposite trends (*i.e.* erosion or accretion), depending on the data used. Thus, it is important to know the variability and magnitude of shoreline changes (in the short-term) to understand the real meaning of rates based on few data points (*i.e.* the end-point method).

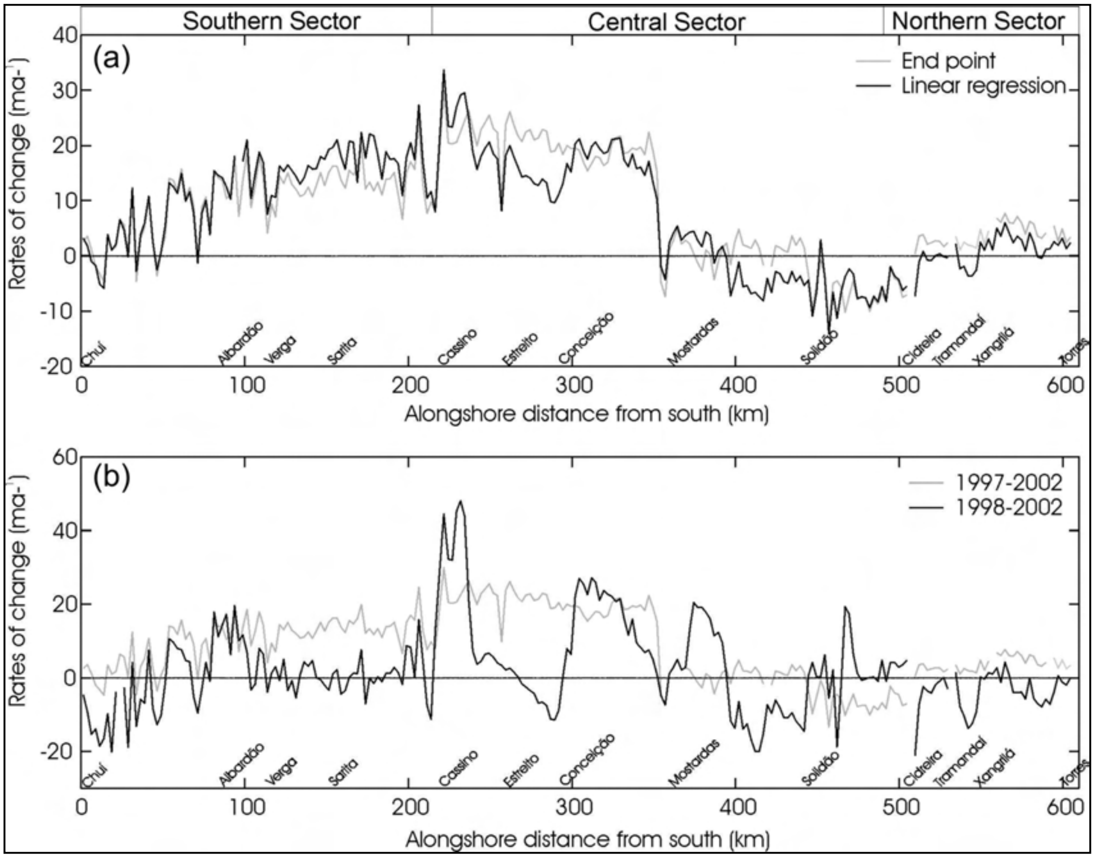

Figure 5.7. Rates of (short-term) shoreline changes estimated for the RS coast based on DGPS shoreline mapping, showing results obtained by (a) the end-point and linear regression methods for the 1997 to 2002 time interval, and (b) the comparison of rates obtained by the end-point method for the periods 1997 to 2002 and 1998 to 2002. *Positive values represent accretion and negative values represent erosion.*

FACTORS INFLUENCING THE ALONGSHORE VARIABILITY OF THE SHORELINE CHANGES

Data presented in the previous sections show that the shoreline responds differently alongshore to seasonal and annual changes. Considering that beaches are complex environments that respond to the interaction of land, sea, and atmospheric processes acting at different temporal and spatial scales, it is difficult to assess which is the dominant factor responsible for a specific observed change. Whilst sometimes it may be possible to identify a major influencing factor over short time periods, it is considered that a combination of factors interacting in a non-linear manner drives beach processes and determines changes in morphology (KOMAR, 1999). This section examines the influences of grain size, shoreline orientation, longshore sediment transport, storms, and ENSO on the seasonal and annual patterns of shoreline change observed in the data.

Grain Size

Generally, RS beaches are composed by well-sorted fine quartzose sands (MARTINS, 1967) with mean grain size around 2.25 Ø to 2.75 Ø (0.15 mm to 0.21 mm). Major differences occur in: (1) Estreito, south of the Conceição Lighthouse in the central sector, where mean grain size vary seasonally from 1.9 Ø to 2.38 Ø (0.19 mm to 0.27 mm) due to the presence of shell fragments (BARLETTA, 2000); (2) the beaches around the Patos Lagoon mouth, where fine sediments reduce the mean size to 2.5 Ø to 2.9 Ø (0.135 mm to 0.18 mm) (SIEGLE, 1996); and (3) between Albardão lighthouse and Hermenegildo (southern sector), where bimodal sediments composed by quartzose fine sands (2.25 Ø or 0.21 mm) and bioclastic gravels (-0.5 Ø or 1.5 mm) occur along a 30-km long segment (CALLIARI and KLEIN, 1993). However, these changes are related to geological settings (*i.e.* fine sediments supplied by the Patos lagoon and shell fragments transported cross-shore from relict underwater deposits to the beach) and do not reflect alongshore differences on the present dynamic processes. Excluding the areas of major changes in the mean grain size, there is a subtle decrease in the mean grain size from south to north along the RS beaches (Figure 5.8), which might be reflecting sorting associated with the net longshore transport of sediment to the north (*e.g.* BIRD, 1996). Additionally, gradients of wave energy along the shoreline as yet undetermined may also contribute to alongshore sediment sorting (*e.g.* CARTER, 1988).

Comparing grain size data presented by SIEGLE (1996) with patterns of shoreline change in the southern sector, it is possible to associate areas of coarser mean grain size (south of Albardão) with lower magnitudes of changes and less alongshore variability, and areas of finer mean grain size with areas of greater changes. In the central sector, both annual lines show a

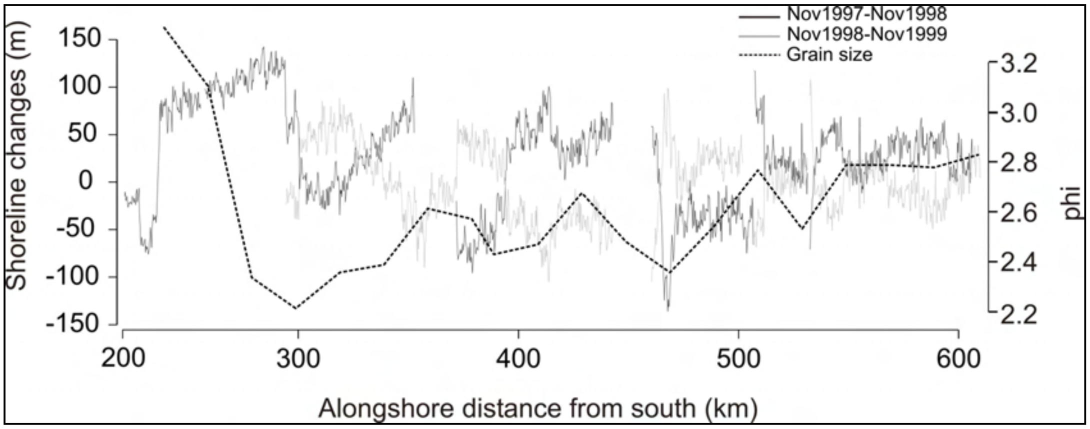

Figure 5.8. Comparison of annual shoreline changes and variations in mean grain size along the central and northern coastal sectors. Observe that the length-scale of the fluctuations observed in the shoreline change lines is similar to the length-scale of the variation in mean grain sizes.

rhythmic pattern alongshore (Figure 5.5) that are similar to oscillations observed in the mean grain size of beach samples collected by the Center of Coastal and Ocean Geological Studies (CECO/UFRGS) every 20 km along the central and northern sectors (Figure 5.8). Although variations are subtle (about 2.2 Ø to 2.8 Ø or 0.13 mm to 0.2 mm), it is noted that the mean grain sizes decrease towards the center of the embayments where shoreline changes are greater. The length-scale of the fluctuations observed in the shoreline movements along the central sector is similar to the length-scale of the variation in mean grain sizes (Figure 5.8). It seems that magnitudes of shoreline changes are strongly related to grain size that in turn is related to the shape of the shoreline, *i.e.* larger changes occur in the embayments where finer grain sizes occur. However, the use of grain size data as a proxy for variability in the shoreline changes should be carefully considered as other factors also interact with them (*e.g.* geological settings, wave energy conditions).

Higher concentrations of heavy minerals have been associated with areas of erosion (*e.g.* ROY, 1999; FRIHY and KOMAR, 1993). Along the RS coastline, SIEGLE (1996) found that areas of high erosion rates present greater percentage of heavy minerals than adjacent non-eroding beaches, such as in Hermenegildo and Bujuru (north of the Patos lagoon mouth). According to DILLENBURG *et al.* (2004), these are the only two significant concentrations of heavy minerals occurring in the RS coast, and both occur where long-term receded barriers dominate. Additionally, preliminary results indicate also a strong correlation between the concentrations of heavy minerals, the long-term evolution of coastal barriers, and rates of LST along the central and northern sectors (CARLA BARROS, CECO/UFRGS, personal communication). In this study, it is observed that concentrations of heavy minerals are higher immediately north of locations where there is a significant increase in the LST (estimated by modeling), which also coincides with areas of long-term coastal retreat.

Shoreline orientation

The RS coastline has a general NE-SW orientation with subtle changes (< 5°) alongshore when short beach segments are considered. However, due to its undulating shape, changes in shoreline orientation in the order of 10° are observed at a regional scale. Such changes in shoreline orientation influence the angle that waves approach the beach face and thus play a major role in determining the direction and magnitude of LST. In order to show the effect of waves approaching from NE, E, ESE, SE, S, SSW, and SW in different coastal orientations, Figure 5.9 shows annual LST predicted for the RS coastline by the CERC formula (USACE, 1984) for wave heights of 0.5 m 1.0 m and 1.5 m. The figure shows that the shoreline orientation affects LST in three ways: (1) the direction of net sediment transport, (2) the magnitude of net transport, and (3) the alongshore variations in the magnitude and direction of net sediment transport. Some waves result in a net transport to the same direction along the entire coastline with only minor differences in the magnitude of rates. This applies to waves from E (90°) and S (180°) that cause intense sediment transport to the south and north, respectively (Figure 5.9). Although waves from NE (45°) and SSW (200°) push transport always to the south and to the north, respectively, they are more effective in some areas than in others, resulting in major changes in the magnitude of transport. It is evident, for example, that embayment areas located south of coastal projections are protected from NE waves ($H_s \leq 1.5$ m), *e.g.* Cassino beach. Interesting to note that SW waves (Hs ≤ 1.5 m) generate a near nil net transport along most of the RS shoreline, resulting in significant net transport only in the beaches north of the Patos Lagoon mouth up to Conceição lighthouse, an area that is subjected to long-term erosion. Other waves result in a more complex LST response (*e.g.* ESE and SE waves), with net transport to the south in some segments, to the north others, and little if any transport in others (Figure 5.9). Figure 5.9 indicates that a combination of waves of differing heights and directions for variable lengths of time could conceivably result in a balance of sediment transport or a nil net rate along some beach segments.

Changes in shoreline orientation also influence the distribution of energy reaching the shore due to wave refraction, which tend to erode coastal projections due to concentration of wave energy and to promote deposition along the embayments due to decrease in wave energy (*e.g.* PETHICK, 1984; KOMAR, 1998). According to DILLENBURG *et al.* (2000), higher wave energy along the projections and less energy along the embayments due to dissipation across a wider shelf are mechanisms influencing strongly the sediment budget along the RS coast in the last 5 ka. The 220-km long southern coastal sector has an undulated shape due to the presence of a large-scale coastal projection from Chuí to Sarita Lighthouse and a large-scale embayment northward of the Sarita Lighthouse. The shoreline responds differently to seasonal changes along the southernmost 90 km (approximately south of Albardão lighthouse) and along the northward segment, from Albardão lighthouse to Cassino beach (Figure 5.4). The area where there is a change in the response of the shoreline corresponds to the apex of a large-scale coastal projection where magnitudes of changes and the variation between the displacement lines tend to be minimum. On the other hand, the largest peaks of change coincide with the central part of the embayment between Cassino and Sarita lighthouse (ESTEVES *et al.*, 2003a). Therefore, it is likely that sediments eroded from the projections are transported alongshore to the embayments thus making a larger volume of sand available to the cross-shore transport. Common with observations along the central sector, the largest shoreline changes in the southern sector were observed in an embayment where finer mean grain sizes occur (as discussed in the previous section).

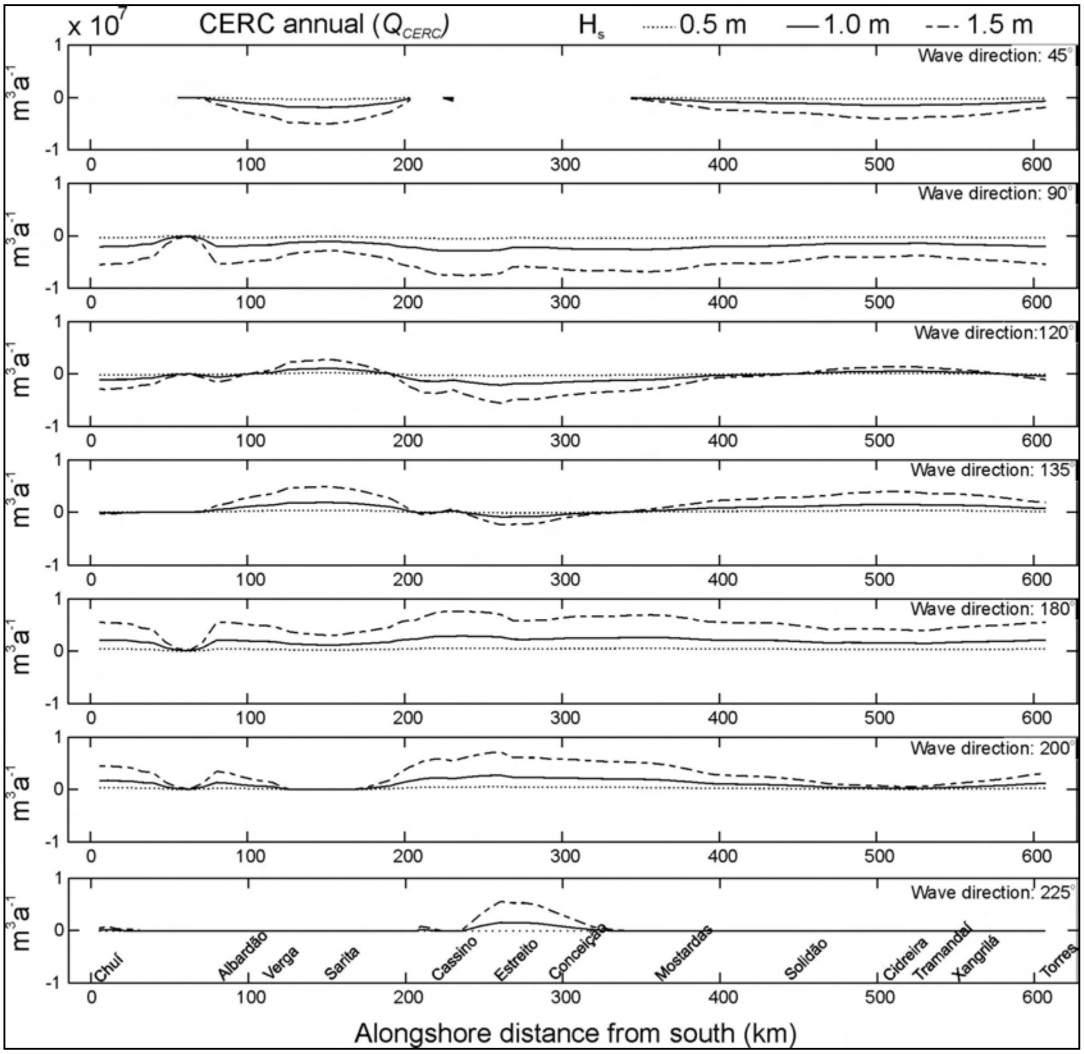

Figure 5.9. Results of annual longshore sediment transport predicted for the RS coast by the CERC formula (USACE, 1984) for the stated wave directions and significant wave heights of 0.5 m, 1.0 m, and 1.5 m. The alongshore variation in the sediment transport indicates the influence of shoreline orientation in the direction and magnitude of net sediment transport.

Storms, cyclogenesis, and El Niño-Southern Oscillation (ENSO)

Storms along the RS coast are more frequent in the fall and winter and are associated mainly with the passage of cold fronts and extratropical cyclones. The stormy season starts in April, when extreme events occur due to the combination of spring tides, high energy waves, and storm surges (CALLIARI *et al.*, 1998). Such combination of high water levels and high wave energy favors erosion in parts of the beach that are not subjected to the waves attack under normal conditions (DOLAN and DAVIS, 1992). Thus, the first fall storms result in intense erosion and large profile changes in RS beaches as they impact onto the accreted beaches formed during the fair-weather conditions in the summer (CALLIARI *et al.*, 1998). Analysis of wind data (daily means) registered in Rio Grande from 1988 to 2003 shows that NE winds dominate in summer (31%) and winter (39%), but the second and third dominant winds are SE (14%) and E (10%) in the summer and SW (24%) and SE (10%) in the winter. Thus, SW winds account for most of the difference in seasonal energy conditions, as they are related to the passage of extratropical cyclones and are involved in 65% of the storm surge events in Rio Grande (SARAIVA *et al.*, 2003). Although MOTTA (1969) reported that wind and wave directions showed no correlation in the Tramandaí dataset, it is likely that the increase in the frequency of SW winds in the fall and winter is associated with storminess, which in turn result in higher wave energy and beach erosion along RS beaches.

Cyclones affecting southern Brazil are generated either in the southern Atlantic Ocean or in the southern Pacific Ocean crossing the Andes towards the Atlantic Ocean (GAN, 1992). In the winter, the sea surface temperature (SST) gradient between the Falkland and Brazil currents enhance the heat flux into the cold air masses moving from the continent to the ocean, intensifying cyclogenesis around 32.5°S to 55°W (GAN, 1992; SINCLAIR, 1995) and increasing the number of cyclones affecting the RS coastline. According to GAN (1992), from 1979 to 1988, cyclones occurred in all seasons, but were more frequent in the fall and winter when 6 and 8 cyclones crossed the Andes, respectively, and 30 were formed in the southern Atlantic Ocean, in average per season.

The atmospheric circulation along the RS is strongly affected by the obstruction of frontal systems propagation that can last from 5 days up to 3 weeks, more frequently in the fall and less frequently in the winter and spring, resulting in longer periods of dry or wet weather (KRUSCHE *et al.*, 2002). Several studies suggest that the obstruction of cold fronts and the associated increase in rainfall in southern Brazil is due to the strengthening and southwards shift of the subtropical jet at higher levels, which occurs in the spring of the initial El Niño year (KRUSCHE *et al.*, 2002; GRIMM, 2003; CAZES-BOEZIO *et al.*, 2003). Other studies show that the enhanced subtropical high-level jet over southern Brazil causes above-normal blocking of frontal systems over southern Brazil also during El Niño winters (*e.g.* NOBRE *et al.*, 1986; AMBRIZZI, 1994).

According to PEZZA and AMBRIZZI (2003), there is a higher anticyclone concentration in the South Atlantic Ocean due to the enhanced Atlantic subtropical high and a high cyclone concentration in southern Argentina during El Niño winters. Similarly, GAN (1992) associated the largest number of cyclones in 1983 (based on the period 1979-1988) with the intensification of the subtropical jet caused by the strong El Niño at that year. The high anticyclone concentration over the South Atlantic during El Niño winters is replaced by a high cyclone concentration in the winter of La Niña years (PEZZA and AMBRIZZI, 2003). Wind data from Rio Grande (RS) show an intensification of wind speeds from all directions and in all seasons in the El Niño year of 1997, especially from the NE, N, and W when compared with 1998 or 1999. However, SW winds are more frequent and stronger during the fall, winter, and spring in 1999 (La Niña year) than in 1997 and 1998, corroborating with the findings of intense cyclogenesis in La Niña years reported by TOZZI (2002).

Changes in the atmospheric circulation driven by the ENSO also affect the wave climate and the longshore currents. Analysis of the longshore current direction obtained through visual observations in Tramandaí (NICOLODI *et al.*, 2000) shows that the current was dominant to SW in 1996 and 1997, shifting to NE in 1998 and 1999, returning to flow to SW in 2000, 2001, and 2002 (Figure 5.10). The reversal in the net direction of longshore currents is coincident with the strong El Niño event of 1997/1998 and La Niña 1998/1999 and might be the main factor driving annual shoreline changes to show opposite signs along the central and northern sectors as presented in figures 5.2, 5.5, and 5.6. The differences in the direction of longshore currents were observed mainly in the fall and spring. From April to July (fall), currents were flowing to SW in 1997 and to NE in 1998 and 1999; in September and October (spring) currents were dominantly to NE in 1997 and to SW in 1998 and 1999, and in November and December currents were dominantly to SW in all years. This suggests that waves from NE and E were dominant in fall 1997, while southerly waves dominate in 1998 and 1999. Although wave data are not available for that period, wind distribution indicates that in fall 1997 NE winds were more frequent (22%) and stronger (mean of 5.4 m/s) than in fall 1998 and 1999 (14%, 3.4 m/s and 2.6 m/s, respectively), and southerly winds were significantly less frequent. For example, SW winds occur in 11% of the time in fall 1997, against 18% in fall 1998 and 23% in fall 1999. Southerly winds were more frequent in September and October 1997 than they were in the fall, while winds from NE and E were the most frequent in the spring of 1998 and 1999.

Therefore, the wind data correlates with the reversal of the longshore currents direction, suggesting that the wave climate responds in a similar fashion to the ENSO effects. Thus, the strong winds registered in 1997, especially from NE, reflects the intensification of the Atlantic

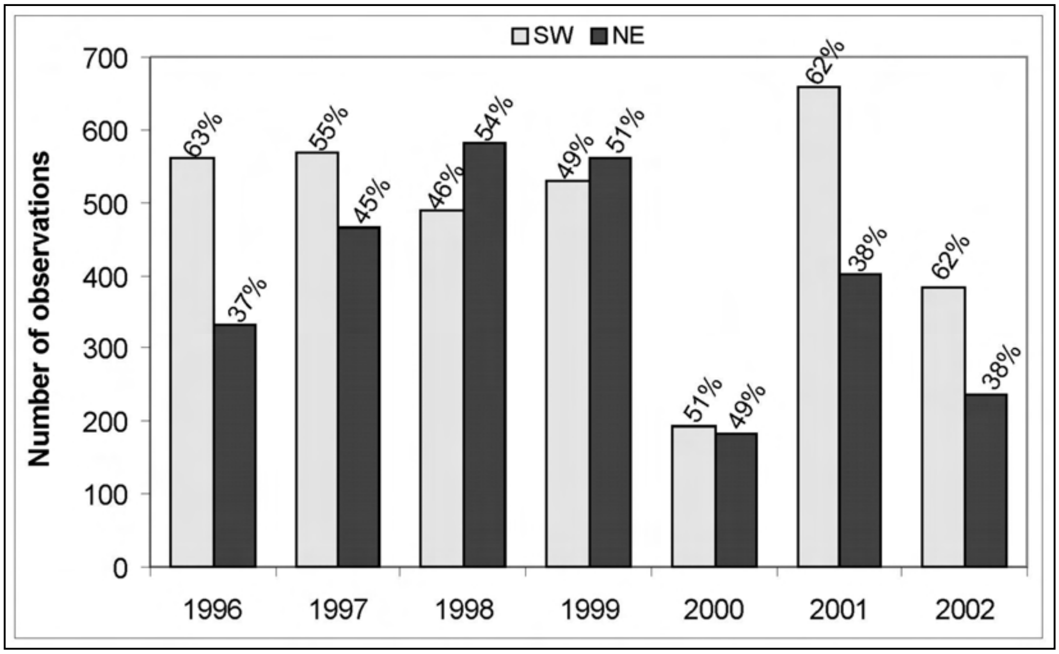

Figure 5.10. Dominant direction of longshore currents obtained through visual observations in the fishing pier of Tramandaí, northern coastal sector. The values on top of each column refer to the percentage of observations available for each year. Note that the current was dominant to SW in 1996 and 1997, shifting to NE in 1998 and 1999, returning to flow to SW in 2000, 2001, and 2002. Data in 2000 was available only from January to May, and in 2002 from January to July.

subtropical high in El Niño years reported by PEZZA and AMBRIZZI (2003). Such high-energy conditions might have resulted in an accentuated shoreline retreat as registered by the DGPS line of Nov1997. On the other hand, the less intense winds, lower waves, and reduced storm surge frequency observed in the winter of 1998 (post El Niño) reported by TOZZI (2002), favored the recovery of the shoreline in 1998 to a more accreted position, as registered in the GPS line of Nov1998. Thus, the El Niño effect would explain the accretion observed from Nov1997 to Nov1998 in the northern sector (Figure 5.6a). Similar results were reported by SOUZA and ANGULO (2003) for the northern coast of Santa Catarina state (southern Brazil), where the largest sand loss and beach retreat from 1996 to 2000 occurred from February to September 1997 and the largest accretion occurred from February to June 1998.

The intensification of cyclone activities in La Niña winters (PEZZA and AMBRIZZI, 2003), reflected by the increase in the number of mid-Atlantic storms in the winter of 1999 (TOZZI, 2002) and by the stronger and more frequent SW winds registered especially in spring months, might have caused the erosion registered from Nov1998 to Nov1999 in the northern sector (Figure 5.6a). LAMOUR and SOARES (2003) have associated a reduction in sand volume in the beaches of northern Santa Catarina in 1996 and 1997 with La Niña and El Niño events, respectively. Studying beaches in the same area, SOUZA and ANGULO (2003) have associated erosion with El Niño in 1997, but have reported accretion due to La Niña from 1998 to 2000. Probably, the accretion observed by these authors is due to the fact that the intensification of cyclogenesis in La Niña year occurs in winter and spring, although winds are generally less strong than in El Niño years. This lower energy conditions might result in an overall beach accretion, especially when comparing profiles from June1998 (winter) and March2000 (end of summer), as conducted in that study. Similarly, BESSA Jr. and ANGULO (2003) have related beach accretion along the southern coast of Paraná (southern Brazil) from February 1999 to March 2000 with lower wave energy during La Niña years. However, their data show a reduction in beach volume from February to November 1999 in ten of the thirteen beach locations, what is in agreement with the erosion observed in RS beaches in the same year.

The southernmost segment of the southern sector responds similarly to the ENSO effects described above, although not as strongly as along the northern sector. The northernmost segment of the southern sector does not show the opposite movements in consecutive years (Figure 5.4) probably due to differences in sediment budget. In this area, the sediment budget is probably highly positive as a net deposition has been reported in the short (*e.g.* CALLIARI and KLEIN, 1993) and long-terms (DILLENBURG *et al.*, 2000). Thus, it is more likely that greater variations in the waves energy and/or direction are required to promote changes in patterns of sediment transport and shoreline movements along that coastal segment. Additionally, the shoreline movements to opposite directions observed along the central sector in the Nov1997-Nov1998 and Nov1998-Nov1999 lines (Figure 5.5) might result from the ENSO influence in southern Brazil through the shifts in the direction of longshore currents.

Longshore sediment transport

There are no published field measurements of LST rates for the RS coast. However, sedimentary and geomorphologic evidences indicate that the net LST is to the north (TOMAZELLI and VILLWOCK, 1992). Visual observations of the longshore current direction registered three times a day at the fishing pier of Tramandaí show that currents are bi-directional (NICOLODI *et al.*, 2000). From March 1996 to July 2002, currents flowing to SW were observed in 55% of the time and currents to NE in 45% of the time. The dominance of currents to SW increases to 60% in spring and summer, while currents to NE are slightly dominant in fall and winter (52%). Similar results are reported by TOZZI (1999) for 5 years of visual observations at Cassino beach. Recently, LST was estimated using the Energy Flux Method (USACE, 1984) and results indicated that the highest rates of LST are coincident with areas of erosion (LIMA *et al.*, 2001). The study showed that the largest LST rates occur in the southern half of coastal projections where the shoreline orientation (N45°E) is close to the optimum angle for LST for E and S waves (Figure 5.9). The rates of LST depend on sediment availability, shoreline orientation, and the height, period, direction, and duration of the waves. Thus, assuming that the volume of sediments is equally available alongshore, the net northward transport results mainly from the difference in energy between NE-E waves and SE-S-SW waves, which are usually higher and associated with the passage of cold fronts.

The reversal in the direction of longshore currents discussed in the previous section might also affect the rates and direction of the net LST along different beach segments. According to the available data, the longshore current generally flows to SW in 62% of the time, but in 1998 and 1999 currents were to SW 46% and 48% of the time, respectively. It is assumed that, in regular years (currents flow to SW in 62% of the time), there is a balance in the net longshore transport (ESTEVES *et al.*, 2004) as waves from the south are less frequent but stronger. Modeling of LST for various combinations of wave heights and directions indicates that a nearly nil net transport can be obtained for a range of scenarios (Figure 5.11). The scenarios for a regular year are based in the following assumptions: (a) NE (45°) and E (90°) waves dominate in 62% of the time and are equally distributed, as observed in the historical wave records presented by COLI (2000), (b) southerly waves occur in 38% of the year, tested for a range of combinations of waves from SE (135°), ESE (120°), S (180°), and SSW (200° and 215°), (c) SSW waves represent storm conditions and do not occur in more than 10% of a year, in agreement with the historical wave record (COLI, 2000) and with data from SARAIVA *et al.* (2003), (d) waves from NE and E are smaller than southerly waves and are tested for H_s varying from 0.5 m to 1.0 m, (e) waves from SSW are the highest and tested for $H_s = 2$ m, (f) S, ESE, and SE waves are tested for H_s from 0.75 m to 2.0 m.

In the scenarios tested for a regular year, the net LST can be dominantly to the north (Figure 5.11a), dominantly to the south (Figure 5.11b), to the same direction in all coastal segments (Figure 5.11c,e,f), or show an approximately nil net transport depending on the combination of waves height and directions (Figure 5.11b,d). The lack of waves and longshore currents measurements impede the verification of the modeling results used here to simulate hypothetical situations based on the (qualitative) data available. Considering a scenario where all southerly waves are represented by SE waves (not illustrated), net LST is mainly to the north when $H_s > 1.25$ m, and almost nil for $H_s = 0.75$ m, except in two sectors: (1) from Chuí to Albardão, where the net transport is almost nil in all cases, and (2) from Cassino to north of Conceição lighthouse, where net transport is to the south. Adding SSW waves to this scenario, there is a reduction in the area showing net transport to the south, shifting completely to the north when 20 days of SSW waves are included and SE waves are $H_s \leq 1.25$ m (Figure 5.11a). The points of divergent net LST migrate alongshore according to the contribution of SSW waves. One of these points is located around the Conceição Lighthouse area (Figure 5.11a,c) where intense erosion has been reported in the short and long-term (*e.g.* BARLETTA and CALLIARI, 2003; TOMAZELLI *et al.*, 1998). The other divergent point is located north of the Patos lagoon mouth, where erosion also has been reported associated to the obstruction of littoral drift by the jetties (*e.g.* LÉLIS and CALLIARI, 2003).

Considering that southerly waves are represented solely by ESE waves, net sediment

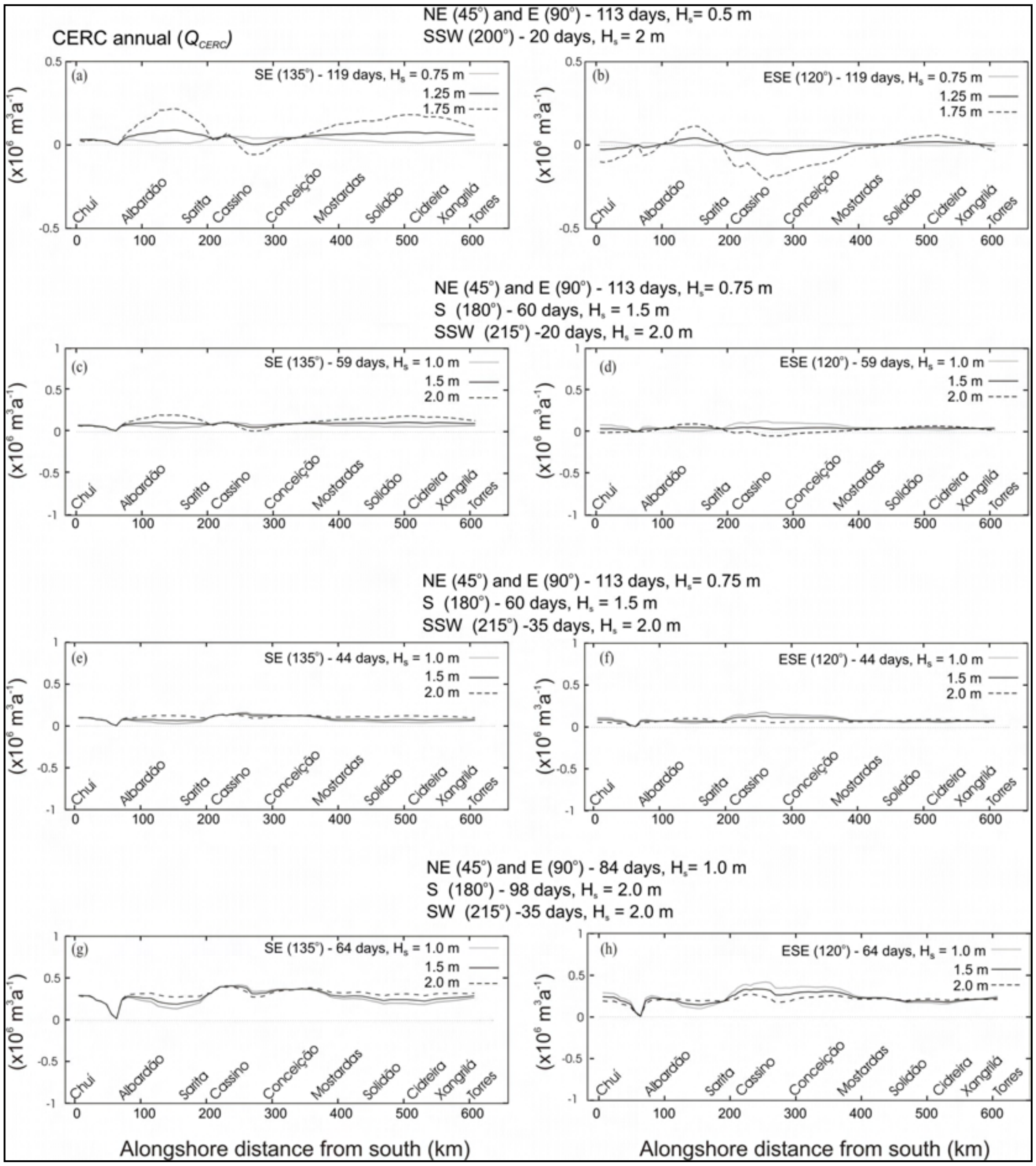

Figure 5.11. Annual rates of net longshore sediment transport predicted for the RS coast by the CERC formula (USACE, 1984) for various combinations of wave heights and directions that simulate conditions in years when the longshore current is dominantly to SW (a,b,c,d,e,f) and years when the current is dominantly to NE (g,h). *Note that the vertical scale is in graphs (a) and (b) differs from the others.*

transport is mainly to the south (not illustrated), except in two sectors where net transport is to the north: (1) north of Albardão to north of Sarita, and (2) from Solidão to Xangrilá. Adding SSW waves to this scenario, net transport also tend to be pushed northwards; however, the divergent points do not migrate alongshore, and more days of SSW waves are necessary to produce net transport to the north along the entire coast, *i.e.* more than 30 days for H_s= 1.25 or 20 days for SE waves of H_s= 0.75 m (Figure 5.11b). A nearly nil net transport was observed after 10 to 15 days of SSW waves for SE waves of H_s= 0.75 m, or after 30 days of SSW waves for SE waves of H_s=1.25 m. A net balance is even more persistent when enhancing NE and E waves to H_s= 0.75 m, although more days of SSW waves are required. In several scenarios, the net LST is to the south in the area north of Cassino up to Conceição lighthouse (Figure 5.11a, b, d). Thus, sediment eroded from areas further north (*i.e.* Conceição lighthouse) might be partly balancing the sediment deficit caused by the obstruction of the northward LST by the jetties of the Patos lagoon; explaining why erosion north of the jetties is not as intense as expected when compared with the accretion observed to the south.

Including S waves in the scenarios described above, the net transport is pushed to the north and there is a trend of smoothing the alongshore differences in the transport rates (Figure 5.11c,d,e,f). In a situation where southerly waves come from S and SE, the net transport is dominantly to the north even for NE and E waves of H_s = 1.0 m. Same results are obtained from the combination of waves approaching from S and ESE, although net transport rates are smaller and do not change significantly when the height of ESE waves increases. A net transport to the south occurs in a short segment in the area of Estreito with the divergence point occurring near the Conceição Lighthouse, similarly to the scenario described in Figure 5.11a. Adding the SSW waves to the scenarios above, net northward transport is enhanced from Cassino to Mostardas and south of Albardão and is slightly reduced in the other areas (Figure 5.11c,d). Increasing the influence of SSW waves from 20 to 35 days, in an attempt to represent intensification of cyclogenesis, net transport is to the north in all coastal segments with a decrease in the volume of net LST, except from Cassino to Mostardas where a slightly increase in volume is observed (Figure 5.11e,f). Thus, modeling results show that in an usual year: (a) net transport rates tend to be less than 200,000 m^3a^{-1}, (b) a net balance is observed in a combination of scenarios, (c) ESE waves push sediment transport to the south from Cassino to Solidão, (d) SSW waves push net transport to the north from Cassino to Mostardas, and (e) the net LST was always to the north from Albardão to Sarita and north of Solidão to Xangrilá (for the tested scenarios), while in the other areas the direction of net transport shifts due to the influence of SE or ESE waves and to the increase in the number of SSW waves days.

Reducing the occurrence of NE and E waves from 62% to 46% of the time, as shown in 1998 and 1999 by the records of littoral drift directions in Tramandaí, modeling results are similar to the last scenarios described above with a slightly greater volume of net LST. However, net transport is to the south from Cassino to Solidão only when wave heights are maintained the same as in the previous scenarios and SSW waves occur in 20 days or less. However, it is likely that wave heights are larger in those years due to the intensification of storminess and more frequent SSW waves. In this case, net transport is always to the north and tends to show rates reaching up to 400,000 m^3a^{-1} (Figure 5.11g,h). Therefore, when currents to NE are dominant, a greater volume of sediment is mobilized especially from the areas with a shoreline orientation more exposed to the SSW waves (*i.e.* south of Albardão and in the Conceição lighthouse area). These sediments are then transported north and deposited in the areas of less potential sediment transport, such as smooth embayments or along a segment of less exposed shoreline angle, as suggested by LIMA *et al.* (2001).

Modeling results thus show that net LST can be to the south or to the north in adjacent coastal segments under certain wave conditions. However, shifts in the direction of longshore currents could not explain the oscillations of shoreline changes registered along the central sector where erosion alternates with accretion in adjacent segments. Such oscillations are more or less coincident with smooth changes in shoreline orientation that also relates with changes in the mean grain sizes (Figure 5.8). Recent studies have suggested that longshore transport tend to increase perturbations in a straight shoreline when the angle between the wave crests and the general shoreline orientation is higher than the angle of maximum sediment transport (MURRAY and ASHTON, 2003; ASHTON *et al.*, 2003), which is slightly greater than 45° (DEIGAARD *et al.*, 1988). According to these studies, the longshore sediment flux converges along the crest of the perturbation causing accretion that enhances it. Thus, while maximum longshore transport tends to smooth irregularities in the shoreline shape (KOMAR, 1998), the highest rates of shoreline changes occur in areas of least sediment transport, especially when deep water waves approach the shoreline at angles just below 80° (MURRAY and ASHTON, 2003). In the RS, the mean shoreline orientation is around 40° along the central sector, favoring the largest perturbation growth (or the maximum shoreline changes) when waves approach from 210° (SSW) and 50° (NE), the strongest and the dominant waves, respectively. It seems that the effects of high angle waves might explain the oscillations in shoreline changes along the central sector; however, further analysis is required to test this hypothesis.

CONCLUSIONS

The RS coastline has been often described as straight and homogeneous leading researchers to accept that results obtained locally are valid for long stretches of the coast. This study has shown that seasonal and interannual variations in the shoreline position exhibit different responses along the three major coastal sectors either in the magnitude of displacements and/or in the time-scale in which the shoreline returns to a previous position. The largest shoreline changes and alongshore variability were registered along the central sector, where areas of erosion alternate with areas of accretion at scales *O*(30 to 90) km, moving to opposite directions in consecutive years. The northern sector is characterized by lower magnitude of changes and less alongshore variability as accretion dominates in one year and erosion dominates in the following year. The southern sector shows a similar response in the southernmost segment and a dominantly seaward displacement of the shoreline in the northernmost sector. Thus, such alongshore variability can only be possible if (1) the RS coastline is not homogenous alongshore, (2) there are gradients of hydrodynamic conditions alongshore, or (3) both.

Results in this study corroborate with previous morphodynamic studies reporting beach accretion due to the fair weather conditions in the spring-summer months and erosion due to the more energetic conditions in the fall-winter months. However, a great variability was observed in the annual shoreline changes registered in November (spring), probably due to the strong ENSO events coincident with the years of shoreline monitoring. In 1997, a strong El Niño event affected the RS coast intensifying winds (and waves) and enhancing storms, resulting in a significant retreat of the shoreline mapped in November. In 1998, the post-El Niño period was characterized by reduction in the wind and wave energy allowing the beach to recover, displacing the shoreline seaward of its 1997 position. The increase in cyclogenesis during the La Niña event of 1999 forced a retreat of the shoreline from its 1998 position. ENSO events strongly affect southern Brazil in the spring months (GRIMM, 2003), when shoreline mapping was conducted in 1997, 1998, and 1999. Therefore, the patterns of annual shoreline change described in this study are probably influenced by the ENSO effects and whether they represent general conditions for that time of the year can only be determined by continued monitoring.

One of the most interesting observations of this study was the presence of a mirror image between the annual displacement lines in the central sector, and between the seasonal lines in the southern sector. The same effect was reported by LIST and FARRIS (1999) comparing shoreline changes along the Outer Banks (North Carolina, US) and Cape Cod (Massachusetts, US) before and after a storm. Thus, as the mirror image has been observed for different beaches on varied short-time scales (after passage of a storm, seasonally, and annually), the return of the shoreline to its previous shape and, perhaps, to its original position, might be just a matter of time. An important question requiring much longer time of observations concerns whether or not such shape and position are dominant through time or merely represent transitory moments between highly dynamic states. Thus, the concept of a mean shoreline position might be questioned for coastlines characterized by large variability where the definition of the most frequent shoreline position at different time-scales may be more appropriate.

The alongshore differences in the response of the shoreline to seasonal and interannual changes is due to a combination of factors interacting in a way that is difficult to ascertain which is more important. The largest shoreline displacements occur in embayment areas and are associated with lower mean grain sizes. Slight variations in the shoreline orientation are coincident with variations in the mean grain size and the rhythmic pattern of shoreline changes in the central and northern sectors, which are also linked with gradients of LST presented by modeling results. The general orientation of the RS coastline favors sediment transport from southerly waves as embayment areas located south of coastal projections are protected from NE waves ($H_s \leq 1.5$ m), which are the dominant along the RS coast. The largest net LST is observed along shorelines more exposed to the stormy SSW waves where erosion has been often reported (*i.e.* south of Albardão and in the area from Estreito to Conceição lighthouse). The alternating erosion and accretion areas observed along the central sector might be an effect of waves approaching to the shore in angles higher than the angle of maximum sediment transport as described by MURRAY and ASHTON (2003) and ASHTON *et al.* (2003). These results are supported by modeling that can only be validated when field measurements become available.

This study has shown that is important to know the variability and magnitude of shoreline changes in the short-term in order to understand the real meaning of rates of change based on few data points (*i.e.* the end-point method). However, rates of change for the RS coast can be estimated only when more data become available. Improved understanding of all the factors driving changes in shoreline position over the wide range of space and time scales is essential for progress in our present ability to predict coastal response to wave climate and changing sea level. To achieve this, it is necessary to instigate a program of field measurements of tides, waves, longshore currents, and sediment transport spanning the RS shoreline with particular attention being paid to areas of large magnitudes of shoreline changes identified here. Such a study will also generate a unique data set of considerable value for calibration, validation, and verification of morphodynamic models at an unprecedented scale.

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CAPÍTULO 6

SHORELINE CHANGES AND COASTAL EVOLUTION AS PARAMETERS TO IDENTIFY PRIORITY AREAS FOR MANAGEMENT IN RIO GRANDE DO SUL

Esteves, L.S. 2004. Shoreline changes and coastal evolution as parameters to identify priority areas for management in Rio Grande do Sul. *Pesquisas***,** submetido.

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Rio Grande, RS

Prezada colega

Acusamos o recebimento do trabalho intitulado "Shoreline Changes and Coastal Evolution as Parameters to Identify Priority Areas for Management in Rio Grande do Sul", de sua autoria, para ser submetido à publicação neste periódico.

Atenciosamente

M Carmo Lima e Cunha

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ABSTRACT

About 80% of the Rio Grande do Sul coastline is undeveloped. The state Program of Coastal Management is incipient and has addressed only the northern coastal sector, which concentrates most of the developed beaches in the state. The central and southern coastal sectors show ideal conditions to the implementation of a regional management plan based on measures that regulate occupation and uses. This study identifies classes of management for RS beaches based on: (a) rates of population growth from 1991 to 2000, (b) intensity of beachfront development and the state of conservation of the beach system, (c) shoreline changes from 1997 to 2002, and (d) coastal evolution in the Holocene. Four classes of management are defined: (1) *critical areas*, are highly developed or show a recent trend of increasing population, are eroding or accreting with large magnitudes of shoreline changes, and require corrective measures; (2) *priority areas*, are low to moderately developed but show a potential for intensification of occupation and uses in the near future, are eroding and show large magnitudes of shoreline movements, they require urgent regulation to restrict development and uses; (3) *areas of future concern*, are not under pressure at present and consist of eroding shores located close to critical or priority areas, regulation measures are recommended, and (4) *natural areas*, are mainly preserved, eroding or accreting, with no signs of changes in the near future. About 198 km (32% of the RS coastal length) are classified as priority areas (located along the central sector), 178 km (29%) as natural areas (in the southern coast of São José do Norte and between Cassino and Albardão), 177 km (29%) as critical areas (northern sector, Cassino, and between Chuí and Hermenegildo), and 65 km (10%) as areas of future concern (beaches from Hermenegildo to Albardão).

Additional Index Words: beach erosion, DGPS, coastal management

INTRODUCTION

The impacts of growing population and development along the coastal zones worldwide have been greatly discussed in the literature (*e.g.* Cendrero, 1989; Turner *et al.*, 1996; Nicholls & Small, 2002; United Nations, 2003). Recent estimates show that 1.2 billion people are living within 100 km of the shoreline in altitudes below 100 m, where population densities are about 3 times higher than the global average (Small & Nicholls, 2003). The low-lying coastal areas are exposed to a variety of natural hazards (*e.g.* Small & Nicholls, 2003; Doornkamp, 1998; Turner *et al.*, 1996) that have caused millions of deaths in the last centuries and are increasingly affecting the economic development of coastal communities as population increases (Small &

Nicholls, 2003). Considering that population growth along the coast is a current process and economic development is desirable, in the last decade major efforts have been applied to implement programs based on *integrated coastal management* (ICM) principles. The ICM aims to define strategies to promote sustainable use, development, and protection of the coastal and marine resources, addressing conflicts of use to search for the harmonization between the physical environment and human activities (Cicin-Sain & Knecht, 1998). However, implementation of ICM requires a certain degree of understanding about the environment from which its interrelationships with socio-economic and cultural assets can be drawn and the potential for use or preservation can be determined.

Understanding coastal processes and beach morphodynamics to forecast shoreline changes in the future is not only a scientific goal but also a requirement to support coastal management plans (Galgano & Leatherman, 1991; Honeycutt *et al.*, 2001; Pajak & Leatherman, 2002). ICM is more efficient when established at a regional scale (Stockdon *et al.*, 2002) mainly because coastal processes are continuous alongshore and changes at one place can cause a range of effects in adjacent coastal and marine environments. Therefore, the need to provide information useful for coastal managers associated with the new technology that allows detailed data collection in large areas resulted in a shift in the interest from local to regional studies. Results from monitoring efforts at a regional scale have supported implementation of management plans at state (such as in the US states of Florida, New Jersey, California, *etc*.) and national levels (such as in the Netherlands). In Brazil, the National Plan of Coastal Management (Plano Nacional de Gerenciamento Costeiro, PNGC) was officially created in 1988 (Law 7.661, from 16/05/88) and detailed in 1990 by Resolution No. 01/90 of the Comissão Interministerial para Recursos do Mar (CIRM). The PNGC is available online at the Ministério do Meio Ambiente (MMA) web site (http://www.mma.gov.br/port/sqa/projeto/gerco/planocac.html). The establishment of the PNGC has increased the interest of government authorities and scientists on coastal monitoring, resulting in the development of several large-scale projects. Examples of integrated coastal projects at national level are *Orla* and *Atlas of Coastal Erosion* (supported by the Ministério do Planejamento) and at a regional/international level there is the project *Coastal Erosion: Causes, Risk Analysis and its Relation with the Genesis of Mineral Resources* (supported by the Organization of the American States), addressing the coast of Rio Grande do Sul (RS), Uruguay, and Argentina (Martins *et al.*, 2002).

The implementation of ICM is a complex process based on the interrelationships between the physical environment, natural resources, societal demands, economic, and cultural aspects (NOAA, http://icm.noaa.gov/story/icm_mgt.html). Thus, this study does not intend to present a comprehensive evaluation of all the major aspects addressed in a management plan. The main goal here is to describe, at a regional level, the present conditions of the RS coast based on factors that are important to define classes of management, including: rates of population growth from 1991 to 2000, intensity of beachfront development, the state of conservation of the dune-beach system, short-term shoreline changes, and coastal evolution in the long term. The RS coast is then classified into four classes of management, defined as areas of critical management, priority areas, areas of future concern, and natural areas.

METHODS

The objective of this study is to define classes of management along the RS beaches based on:

(1) rates of population growth from 1991 to 2000 provided by the *Instituto Brasileiro de Geografia e Estatística* (IBGE), available at http://www2.ibge.gov.br/pub/Censos/Censo_Demografico_2000),

(2) intensity of beachfront development and the state of conservation of the beach system according to data presented in Esteves *et al.* (2003a). In this study, developed beaches refer to areas where at least 30% of the beachfront length is developed,

(3) shoreline change rates estimated for the period 1997 to 2002 by the linear regression method applied to shoreline position data obtained from DGPS monitoring (Esteves *et al.*, 2003b, 2004a), and

(4) coastal evolution in the Holocene according to Dillenburg *et al.* (2000).

Considering the parameters above, a regional analysis was conducted to classify the RS beaches into four classes of coastal management as follows:

I. **Critical areas** include highly developed beaches that show a recent trend of increasing population growth, occupation, and use; are subjected to erosion and/or destruction of coastal structures during storms or are accreting but magnitudes of shoreline changes exceed the mean width of the dry beach; foredunes were destructed or considerably reduced; corrective management is required.

II. **Priority areas** are under growing pressure where urge the implementation of management plans based on regulation and restriction of development and uses; coastal development can be low or moderate; rates of population growth are usually above the state's average; there is evidence of recent intensification of uses (tourism, values of real estate, demand for resources, conflicts of uses); beaches are eroding in the long or short term and show large magnitudes of shoreline movements. Priority areas usually are (a) adjacent to areas of ecological importance (*i.e.* National Parks), (b) close to critical areas, and/or (c) had access recently facilitated or created.

III. **Areas of future concern** have a preserved or nearly preserved beach/dune system; are mainly undeveloped; are usually eroding or show large magnitudes of shoreline movements; are not under great pressure at present but preventive measures are recommended to avoid development in hazardous areas.

IV. **Natural areas** have their natural characteristics preserved, are undeveloped, show low pressure of use and no signs of increasing pressure in the near future, and can be eroding, stable or accreting.

STUDY AREA

The RS shoreline is dominated by exposed sandy beaches. This shore is part of a large coastal plain that was formed and shaped by Quaternary sea level fluctuations resulting in a complex system of coastal lakes and lagoons (Villwock *et al.*, 1986). The lagoon system traps sediments from fluvial discharge, reducing the sand volume reaching the shore (Tomazelli *et al.*, 1998). Waves are the main hydrodynamic process along the RS coast where the maximum tidal variation is 0.5 m (Tomazelli *et al.*, 1998). Waves from east and northeast dominate but southerly waves are the strongest and determine a net longshore sediment transport to the north (Esteves *et al.*, 2004a). This coast is often affected by storms associated with the passage of cold fronts, especially in fall and winter months (Calliari *et al.*, 1998).

In the State Program of Coastal Management (GERCO/RS), the State Foundation of Environmental Protection (Fundação Estadual de Proteção Ambiental, FEPAM) divided the RS coast into four major sectors: (a) the northern, (b) the central-east, and (c) the southern include coastal municipalities along the ocean and municipalities that are adjacent to them, and (d) the central-west includes municipalities along the western margin of the Patos Lagoon (FEPAM, 2000). This study addresses only the 16 municipalities along the ocean coast, dividing them according to the GERCO/RS sectors, except that Rio Grande is included in the southern sector. Thus, here the RS coast is divided into three sectors (Fig. 6.1): (1) the northern sector extends about 120 km south of the Santa Catarina state border and includes the highly developed beaches of Torres, Arroio do Sal, Terra de Areia, Capão da Canoa, Xangrilá, Osório, Imbé, Tramandaí, Cidreira, and Balneário Pinhal; (2) the central sector comprises the mainly undeveloped beaches of Palmares do Sul, Mostardas, Tavares, and São José do Norte, and is limited south by the Patos Lagoon inlet, and (3) the southern sector extends 220 km from the Patos Lagoon inlet to Chuí at the Uruguayan border, and includes the shores of Rio Grande and Santa Vitória do Palmar. Aspects of population growth, beachfront development and uses, coastal evolution, and shoreline changes in the short-term are described in the next sections.

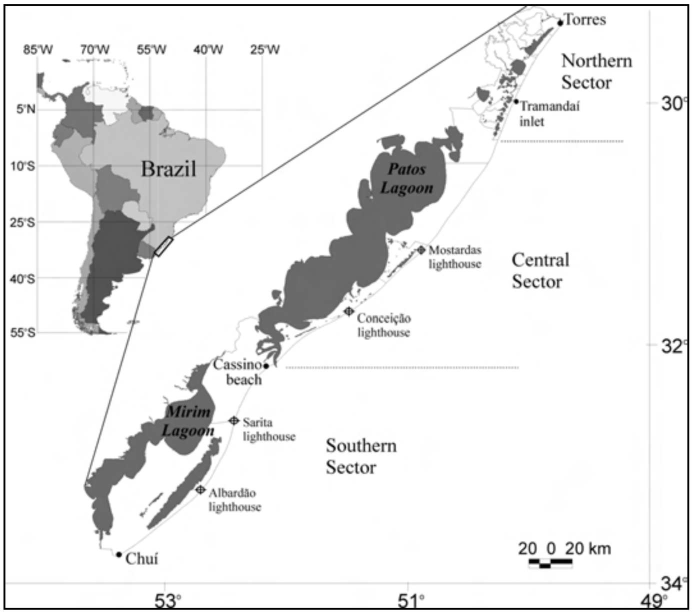

Figure 6.1. The study area showing three major coastal sectors of Rio Grande do Sul: (a) northern, (b) central, and (c) southern.

COASTAL POPULATION GROWTH IN RIO GRANDE DO SUL

The encroachment of population along the coast is a world process that has been aggravated with time, increasing the number of people exposed to natural hazards (*e.g.*, Nicholls & Small, 2002). Brazil is no exception to the rule, as population density decreases considerably from east to west and from south to north (Moraes, 1995). A regional analysis indicates that the non-coastal Northern and Central-West regions presented the fastest population growth in Brazil from 1991 to 2000. However, a detailed analysis shows that the coastal population grew faster than the average of their respective states, except in Pará, Rio de Janeiro, and Sergipe. The RS can be described as atypical amongst other Brazilian coastal states, as colonization started inland and population density at the coast is lower than the state's average (Moraes, 1995). At present, only about 4.5% of the RS population live in coastal cities, but seven of the ten municipalities showing larger population growth from 1991 to 2000 are located at the coast (Esteves *et al.*, 2003a). These municipalities show mean annual rates of population growth four to six times greater than the state's average, representing an increase from 54% to 91% of their total population (Table 6.1).

Considering the mean annual rates of population growth from 1991 to 2000, the sixteen coastal municipalities in RS can be divided into three groups: (1) group I includes the seven municipalities showing rates above 4%: Balneário Pinhal, Cidreira, Tramandaí, Imbé, Xangrilá, Capão da Canoa, and Arroio do Sal (all located in the northern sector); (2) group II comprises four municipalities showing rates of population growth around 2-3% (still above the state's average) and includes: Torres and Osório (in the northern sector) and Mostardas and Palmares do Sul (in the central sector); and (3) group III includes municipalities showing rates of population growth between 0.5% and 1.1% (below the state's average), which are Terra de Areia, Tavares, São José do Norte, Rio Grande, and Santa Vitória do Palmar (Table 6.1). It is clear from these groups that the geographic location along the coast strongly determines the rate of population growth in RS coastal municipalities. The ones included in group I are all located in the northern sector (and are amongst the ten fastest growing in the state). Conversely, the four southernmost coastal municipalities are included in group III (Tavares, São José do Norte, Rio Grande, and Santa Vitória do Palmar).

Table 6.1. Fixed population and rates of population growth for the sixteen coastal municipalities in Rio Grande do Sul for the period 1991 to 2000.

Group	Municipalities (ranking of population growth in the RS)	Population		Rates of population growth from 1991 to 2000 (%)	
		1991	2000	Annual geometric mean	Overall
	Brazil	**146,825,475**	**169,799,170**	**1.64**	**15.65**
	Rio Grande do Sul	**9,138,670**	**10,187,798**	**1.23**	**11.48**
I	Balneário Pinhal (1)	3,892	7,452	7.56	91.47
	Cidreira (2)	4,979	8,882	6.71	78.39
	Arroio do Sal (3)	3,031	5,273	6.41	73.97
	Imbé (4)	7,352	12,242	5.89	66.51
	Capão da Canoa (7)	19,473	30,498	5.16	56.62
	Xangrilá (8)	5,282	8,197	5.05	55.19
	Tramandaí (9)	20,130	31,040	4.98	54.20
II	Mostardas (34)	9,089	11,658	2.83	28.26
	Palmares do Sul (56)	8,836	10,854	2.33	22.84
	Torres (61)	25,423	30,880	2.20	21.46
	Osório (66)	30,050	36,131	2.09	20.24
III	Terra de Areia (144)	10,407	11,453	1.08	10.05
	Rio Grande (166)	172,422	186,544	0.89	8.19
	São José do Norte (169)	22,071	23,796	0.85	7.82
	Santa Vitória do Palmar (186)	31,240	33,304	0.72	6.61
	Tavares (201)	5,075	5,342	0.58	5.26
	Coastal municipalities	**378,752**	**453,546**	**3.46**	**19.75**
	Inland municipalities	**8,759,918**	**9,734,252**	**0.36**	**11.12**

Data source: Population Census of 1991 and 2000 (IBGE)

COASTAL DEVELOPMENT AND USES

Only 19.9% or 123.4 km of the RS coastline is developed with urban centers concentrated mainly in the northern coastal sector (Table 6.2). Few urban areas and small fishing villages account for less than 30 km of developed beaches present along the southern and central coastal sectors. The difference in the intensity of development along the state shoreline is due to two factors: (a) the distance from the largest populated areas in RS (*i.e.*, the metropolitan area of Porto Alegre and the Northeast region), and (b) the facility of road access to the coast (Esteves *et al.*, 2003a). The northern coastal sector is close to the most densely populated areas of the state and can be easily reached at least by two fast routes (BR101 or RS786). The central sector is located in a coastal barrier that separates the Patos Lagoon of the Atlantic Ocean (Fig. 6.1), so the access from inland to the coast is impeded by the presence of the lagoon. In the north-south direction, the central sector can be reached through the recently paved BR101 (except the southernmost 50 km) linking Mostardas and Tavares to the northern sector. The beaches of São José do Norte can only be accessed driving along the beach or through the unpaved BR101 which is well-known due to its bad conditions especially after rainfalls. The southern sector is located in one of the least developed areas of the RS, and access exists only to the developed beaches of Cassino (at the northernmost end), Hermenegildo, and Chuí (at the southernmost end). West-east access to most of this shoreline is hampered by the presence of Mangueira lagoon and large wetlands (*i.e.*, Taim). So the only access to about 200 km of undeveloped coastline is driving along the beach.

Table 6.2. Classification of the Rio Grande do Sul shorelines according to the length of developed shorelines, development on top of the dunes, afforestation, and altered (impacted) shores.

Coastal Sector	Length	Developed beaches		Developed Dunes		Afforestation		Altered Shores	
	km	km	%	km	%[1]	km	%	km	%
Northern	123	94.3	76.7	51.6	54.7	47.7[2]	38.8	98.1	79.8
Central	275	21.1	7.7	10.6	50.2	59.3	21.6	40.3	14.7
Southern	220	8.0	3.6	4.2	52.5	63.7	28.9	56.7	25.8
Total	618	123.4	19.9	66.4	53.8	170.7	27.6	195.1	31.6

[1] Percentage refers to the length of urbanized shores

[2] Includes landscaping at the dunes and introduction of exotic vegetation

Modified from Esteves *et al.* (2003a)

Coastal development in the northern sector consists mainly in second houses which are occupied only in the summer months, when seasonal population increases considerably. Thus, most services and business are active only from December to March, responding to the fluctuations in the seasonal population. Along the central sector, fishing villages are more important than tourist resorts and tourism along this shoreline is often related to fishing activities. One of the major attractions in the central sector is the Lagoa do Peixe National Park, one of the most important sanctuaries of migratory birds in South America (Ramsar, 2002). This Park has an area of 34,400 ha where 182 species of birds can be seen, including 26 species of migratory birds from the Northern Hemisphere and 5 species from the Southern Hemisphere, apart from other animals such as capivaras (*Hydrochoerus hydrochoeris*) and one endangered species of alligator (*Caiman latirostris*). Despite its natural attractions, the Park receives only about 2,500 visitors per year (Ramsar, 2002), probably due to the difficult access and the lack of infrastructure for tourists. In the southern sector, Cassino beach concentrates beach goers from inland cities located in southern RS, while Hermenegildo and Balneário Chuí are occupied by local population of Santa Vitória do Palmar and Chuí, respectively, and few tourists from Uruguay. Traffic along the beach is common between these beaches. In this sector, there is the Taim Ecological Station, a wetland protected by law that serves as natural habitat for wildlife, including migratory birds, capivaras, and the endandered *Caiman latirostris*.

About 54% of the beachfront properties in RS were built on top of the dunes (Table 6.2), resulting in the removal of the vegetation and partial or total destruction of the frontal dunes. Coastal protection works such as revetments and seawalls are a common sight along retreated beaches (*i.e.* Cidreira, Balneário Pinhal, and Hermenegildo), especially where frontal dunes were destructed. In some beaches, projects of dunes reconstruction have been implemented (*i.e.*, Atlântida Sul, Imbé, and Cassino). Afforestation of *Pinus elliotis* too close to the beach is another activity that has been affecting the local water table (Seeliger *et al.*, 2000) and dunes dynamics (Silva & Tagliani, 2000) along the southern and central sectors. The impact of such activity on the sediment balance in the short and long terms is still unknown. Extraction of heavy minerals from the dunes in the area of Bujuru (central sector) is another potential impact on the local beach system. In 1998, a project to extract ilmenite from the dunes in Bujuru (an investment of about U$ 516 million to produce synthetic pigments of rutile and titanium) was halted by federal attorneys (*Ministério Público Federal*) due to environmental concerns. Another economic activity that affects the RS shoreline is the development of the Port of Rio Grande located at the Patos Lagoon estuary. It is the third largest port in Brazil and the most important for the trade between MERCOSUL countries. At present, the two 4-km long jetties that fix the navigation channel are scheduled to be extended in association with the deepening of the channel to allow larger ships to access the port. Therefore, although the RS coastline is mainly undeveloped, according to Esteves *et al.* (2003a) several human activities have impacted this shore, altering the natural conditions along 31.6% of its length (Table 6.2). According to the FEPAM, the major environmental problems along the RS coast are: (1) drainage of wetlands (for irrigation purposes), (2) removal of the dunes vegetation, (3) destruction of the active dunes, (4) afforestation of exotic plants, (5) unplanned occupation along the lagoon margins, (6) drainage, land reclamation, and private ownership of the lagoon margins and wetlands, (7) water pollution by domestic sewage, (8) inadequate agriculture and use of pesticides in areas occupied by the Atlantic Forest, (9) pressure of urban, industrial, and port development on the Patos Lagoon, (10) conflicts on the demand of water usage, and (11) solid waste management (FEPAM, http://www.fepam.rs.gov.br/qualidade/litoranea.asp).

SHORELINE CHANGES IN THE LONG AND SHORT TERMS

The long-term changes in shoreline position are presented here as the evolution of coastal barriers in the last 5 ka described by Dillenburg *et al.* (2000). Data on short-term shoreline changes are based on (a) DGPS shoreline monitoring from 1997 to 2002 (Esteves *et al.*, 2003b, 2004a) and (b) analysis of aerial photos taken in 1974, 1989, and 2000 (Esteves *et al.*, 2004b). Results from these studies are summarized here to describe the long-term trends and short-term magnitudes of the shoreline changes in RS.

According to Dillenburg *et al.* (2000), progradation of coastal barriers in the Holocene occurred along concave shorelines (large-scale coastal embayments) where substrate is gentler, and barrier retreat occurred along convex shorelines (projections) where substrate is steeper. Thus, the alongshore variability in the barriers behavior can be explained by long-term gradients of wave energy caused by the shape of the shoreline and the steepness of the inner shelf (Dillenburg *et al.*, 2004). In the northern sector, a long-term barrier progradation was observed from Torres to Tramandaí and stability from Tramandaí to Mostardas (Dillenburg *et al.*, 2000). Rates of shoreline change obtained from the DGPS monitoring and from aerial photos also show beach accretion from Torres to Xangrilá although indicate a trend to stability from Xangrilá to Tramandaí and to erosion southwards (Esteves *et al.*, 2004b). These results suggest that the area from Xangrilá to Tramandaí represents a transition between the barrier to the north that is accreting in the long and short terms and the barrier to the south that is stable in the long term and eroding in the short term. This shift in the trends of coastal changes is also evidenced by the width of the modern transgressive dune fields (Esteves *et al.*, 2004b). South of Xangrilá the transgressive dune fields are wider then in the north, covering the entire Holocene barrier and extending on top of the Pleistocene barrier from Tramandaí to Mostardas (Dillenburg *et al.*, 2000; 2004).

Along the central sector, receded barriers dominate from Mostardas to Estreito while progradation occurred from Estreito to Verga lighthouse in the Holocene (Dillenburg *et al.*, 2000). Evidence of long-term erosion in this segment includes exhumation of relict lagoonal muds and peat along 60 km of beaches around the Conceição lighthouse to Estreito and the destruction of the Conceição lighthouse during a storm in 1993, where foredunes scarps have retreated in an average rate of 2.5 m a^{-1} from 1975 to 1995 (Tomazelli *et al.*, 1998). Analysis of DGPS data shows that annual shoreline changes along the central sector are characterized by oscillatory movements, with alternating adjacent areas of erosion and accretion occurring at scales in the order of 30 km to 90 km (Esteves *et al.*, 2004a). Thus, rates of change in the short-term vary accordingly to the time interval comprised by the data, especially when estimated by the end-point method (Esteves *et al.*, 2003b, 2004a). Accretion was observed from 1997 to 2002 along the beaches from Conceição lighthouse to Estreito, while erosion was registered when rates were estimated by the end-point method for the 1998 to 2002 period (Esteves *et al.*, 2004a). Additionally, magnitudes of changes tend to be greater along the central sector than in the other coastal segments, enhancing the importance of short-term changes to define management strategies for this sector.

In the southern sector, long-term coastal evolution was dominated by progradation in the embayment between Estreito and Verga lighthouse, stability from Verga to Albardão lighthouse, and erosion from Albardão to Chuí (Dillenburg *et al.*, 2000). In the short term, accretion was registered from Estreito to Albardão while alternating areas of erosion and accretion in the order of 200 m to 1.5 km occur south of Albardão. In the area of Hermenegildo beach, a 5-km long erosion spot is present (from 10.3 km to 15.3 km north of Chuí). Longer segments showing accretion (in the order of 6 km and one 19-km long segment) occur in a 40-km long coastal stretch starting at 36 km north of Chuí. This segment is coincident with the area known as *Concheiros do Albardão*, where bimodal sediments formed by fine sands and bioclastic gravel (shell fragments) dominate (Calliari & Klein, 1993).

IDENTIFICATION OF MANAGEMENT CLASSES

In this section, RS beaches are classified into four classes of management according to their present conditions of population growth, coastal development and uses, coastal evolution, and short-term shoreline changes as described above. Classes of management are: (1) critical, (2) priority, (3) future concern, and (4) natural, which are detailed in the Methods section. The analysis was conducted in a municipal to regional level and the results are presented in five maps at the approximate scale of 1:450,000 for the northern (Fig. 6.2 and 6.3) and central sectors (Fig. 6.3 and 6.4) and 1:400,000 for the southern sector (Fig. 6.5 and 6.6).

Northern Sector

Municipalities along the northern coastal sector show rates of population growth higher than the state's average, (groups I and II, Table 6.1), Terra de Areia (group III, Table 6.1). Observe that the two lowest rates of population growth in the northern sector (Osório and Terra de Areia) occur in municipalities that have the shortest shoreline length in the state, only 3-km long (Table 6.3), indicating that they might be less dependent on beach activities than other coastal municipalities. About 77% of the beachfront along the northern sector are moderately or highly developed and beach uses are intense in the summer months, resulting in a shoreline that is mainly altered (Table 6.2). About 55% of beachfront development occurs in foredunes areas (Table 6.2), which have been totally removed along the most intensely developed beaches, such as Tramandaí, Imbé, and Capão da Canoa. In eroding beaches, constructions on top of the foredunes are usually protected by seawalls or revetments such as in Cidreira and Balneário Pinhal. Undeveloped beaches consist mainly in short segments (usually 300 m to 500 m long) between adjacent developed areas, although longer segments exist as shown in figure 6.2.

Beaches in the northern sector are classified as areas of critical management (Fig. 6.2

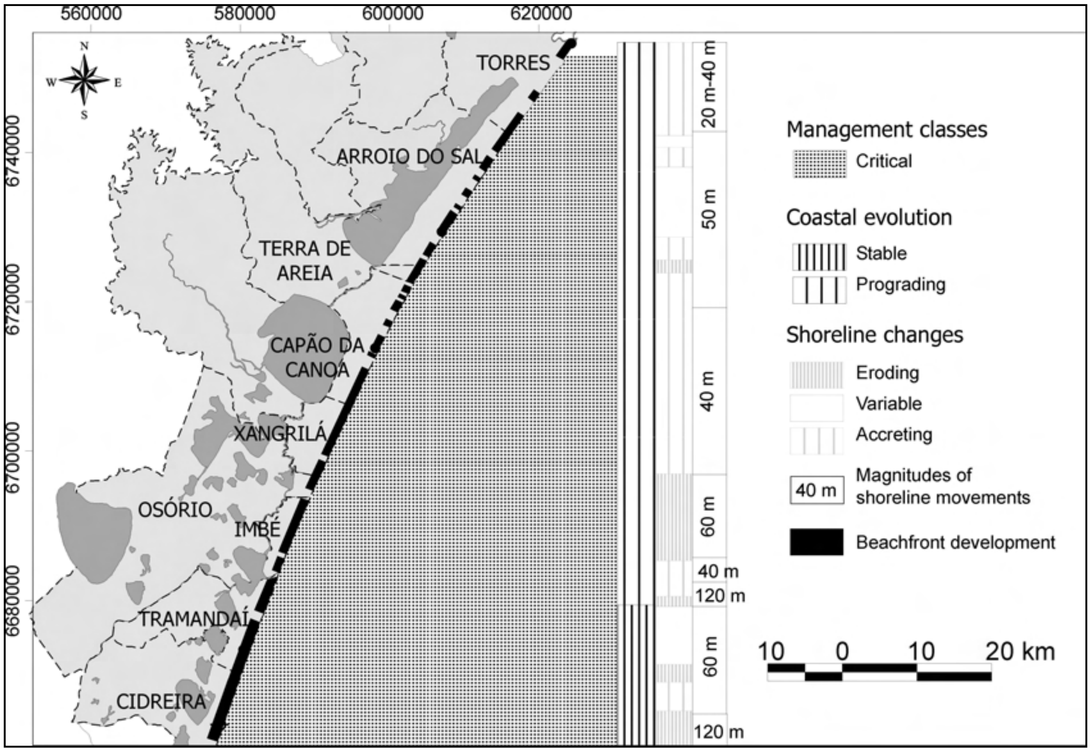

Figure 6.2. Beaches from Torres to Cidreira (northern coastal sector) are classified as areas of critical management. These beaches are highly developed, mainly prograding in the long term, while eroding beaches dominate south of Xangrilá in the short term. Areas presenting alternating short segments of erosion and accretion are represented as areas of variable shoreline changes.

and 6.3), where corrective measures are already needed to mitigate impacts of unplanned occupation. However, these beaches show different trends of shoreline change in the long and short terms. Figure 6.2 shows that a long-term barrier progradation dominates along the northern coastal sector with a trend to stability south of Tramandaí (Dillenburg *et al.*, 2000), while shoreline changes in the short term indicate beach accretion dominating from Torres to Xangrilá and erosion to the south (Esteves *et al.*, 2003b). It is worth to emphasize that alternating areas of erosion and accretion occur along this shoreline, so short segments of eroded beaches occur in the areas where accretion dominates and *vice-versa*. Due to restrains of the scale, alternating areas of erosion and accretion are represented in figure 6.2 as areas of variable shoreline changes. Table 6.3 shows mean annual rates of shoreline change estimated for the 1997 to 2002 period for each coastal municipality and discriminate the length and percentage of accreted, eroded, and stable segments. From Torres to Xangrilá, the mean shoreline change rates are always positive (accretion), and eroded segments occur in less than one third of the shoreline length (Table 6.3). From Osório (Fig. 6.2) to Balneário Pinhal (Fig. 6.3), mean annual rates are negative (erosion) and eroded segments occur along most of the shoreline length, except for Tramandaí that has a mean annual rate equal zero and erosion in nearly 45% of the shoreline length (Table 6.3). Additionally, magnitudes of shoreline change tend to be larger from Cidreira to the south than along the northernmost beaches (Esteves et al, 2004a) as displayed in figures 6.2 and 6.3. Therefore, coastal management needs to be addressed differently and implemented more urgently in the area of Osório to Balneário Pinhal than in the beaches from Xangrilá to Torres.

Central Sector

At present, only 21.1 km or 7.7% of the shoreline along the central sector is developed (Table 6.2), concentrated mainly along the beaches of Palmares do Sul and few small fishing villages spread to the south (Fig. 6.3). The two northern municipalities, Palmares do Sul and Mostardas, had mean annual rates of population growth above 2% from 1991 to 2000 (group II, Table 6.1), while the two southern municipalities, Tavares and São José do Norte, showed rates of population growth below 1%, amongst the lowest along the coast (group III, Table 6.1). Access to these beaches was difficult until 1998 when the BR101 started to be paved linking Palmares do Sul and Mostardas to the most populated areas in the state. According to Page (1998), intensification of tourism and recreation depends on the transport infrastructure, in a way that easy access and good road conditions usually result in over exploitation of resources. Thus, the recently paved road provides easy access to the mainly undeveloped shore of Palmares do Sul, Mostardas, and Tavares what might enhance tourism and development in a pristine area characterized by dunes, wetlands, and lagoons, including the Lagoa do Peixe National Park.

Conversely, the unpaved southernmost 50 km of the BR101 makes access difficult to the beaches of São José do Norte inhibiting development and tourism in this area.

Table 6.3. Mean annual rates of shoreline change and distribution of accreted, eroded, and stable beach segments in RS from 1997 to 2002.

	Length km	Rates[1] ma^{-1}	Accretion km	Erosion km	Stable km	Accretion % of length	Erosion % of length	Stable % of length
Torres	11.5[2]	3.6	10.5	1.0		91.3	8.7	
Arroio do Sal	21.0	1.5	13.1	7.0	0.9	62.4	33.3	4.3
Terra de Areia	3.0	2.3	2.2	0.5	0.3	73.3	16.7	10.0
Capão da Canoa	18.5	3.7	17.0	1.0	0.5	91.9	5.4	2.7
Xangrilá	10.5	1.2	7.0	3.0	0.5	66.7	28.6	4.8
Osório	3.0	-3.7		3.0			100.0	
Imbé	11.0	-0.7	3.0	8.0		27.3	72.7	
Tramandaí	14.5	0.0	6.5	8.0		44.8	55.2	
Cidreira	15.5	-3.6	3.0	12.5		19.4	80.6	
Baln. Pinhal	9.0	-3.5		8.5	0.5		94.4	5.6
Northern	117.5	0.8	62.3	52.5	2.7	53.0	44.7	2.3
Palmares do Sul	23.0	-7.6		23.0			100.0	
Mostardas	90.0	-4.3	13.0	77.0		14.4	85.6	
Tavares	49.0	7.6	40.5	6.0	2.0	82.7	12.2	5.1
SJ Norte	113.0	18.4	113.0			100.0		
Central	275.0	6.6	166.5	106.5	2.5	60.5	38.5	
Rio Grande	64.0	14.0	64.0			100.0		
Sta Vitória	156.0	9.7	132.5	23.5		84.9	15.1	
Southern	220.0	11.9	196.5	23.5		89.3	10.7	
RS	612.5	7.5	425.3	182.0	5.2	69.4	29.7	0.8

[1] Rates of shoreline change estimated through linear regression

[2] The northernmost 5.5 km of beaches were not considered in this study

Similarly to Cidreira and Balneário Pinhal (Fig. 6.3), the coastline of Palmares do Sul and Mostardas have been stable in the long term and are eroding in the short term (Table 6.3), while from Mostardas to Estreito the barrier has been eroding in the long term (Fig. 6.4) and accreting in the short term (Table 6.3). Important to reinforce here that shoreline changes along the central sector are characterized by alternating areas of erosion and accretion that have shown opposite trends in consecutive years (Esteves *et al.*, 2004a). Considering that 100% of the Palmares do Sul shoreline is eroding (Table 6.3), its high rate of population growth (Table 6.1), the potential for increasing pressure in the next few years due to the proximity of the developed beaches of the northern sector, and the recently paved road, this shore is classified as critical areas (Fig. 6.3). The mainly undeveloped beaches from Mostardas (Fig. 6.3 and 6.4) to Estreito in São José do Norte (Fig. 6.4) are classified as priority areas. Unplanned occupation in these areas should be avoided through delimitation of risk zones and setback lines for coastal constructions because these beaches (a) are eroding in the short (*i.e.* Mostardas) or in the long term (*i.e.* from Mostardas to Estreito), (b) are subject to large magnitudes of shoreline changes, (c) show lower pressure of development and less impacted beaches but the recently paved BR101 has facilitated access to an area of pristine beaches, (d) are adjacent to areas of environmental protection (*i.e.* Lagoa do Peixe National Park), or (e) show potential for mineral extraction (*i.e.,* heavy minerals in Bujuru). Beaches south of Estreito are accreting in the short and long terms, are mainly undeveloped, show low rates of population growth, and have difficult access. These characteristics indicate natural areas (Fig. 6.4) showing low risk of increasing pressure in the near future. However, these beaches should be monitored to evaluate the effects of afforestation near the dunes and the impact of the jetties at the Patos Lagoon mouth on the sediment budget.

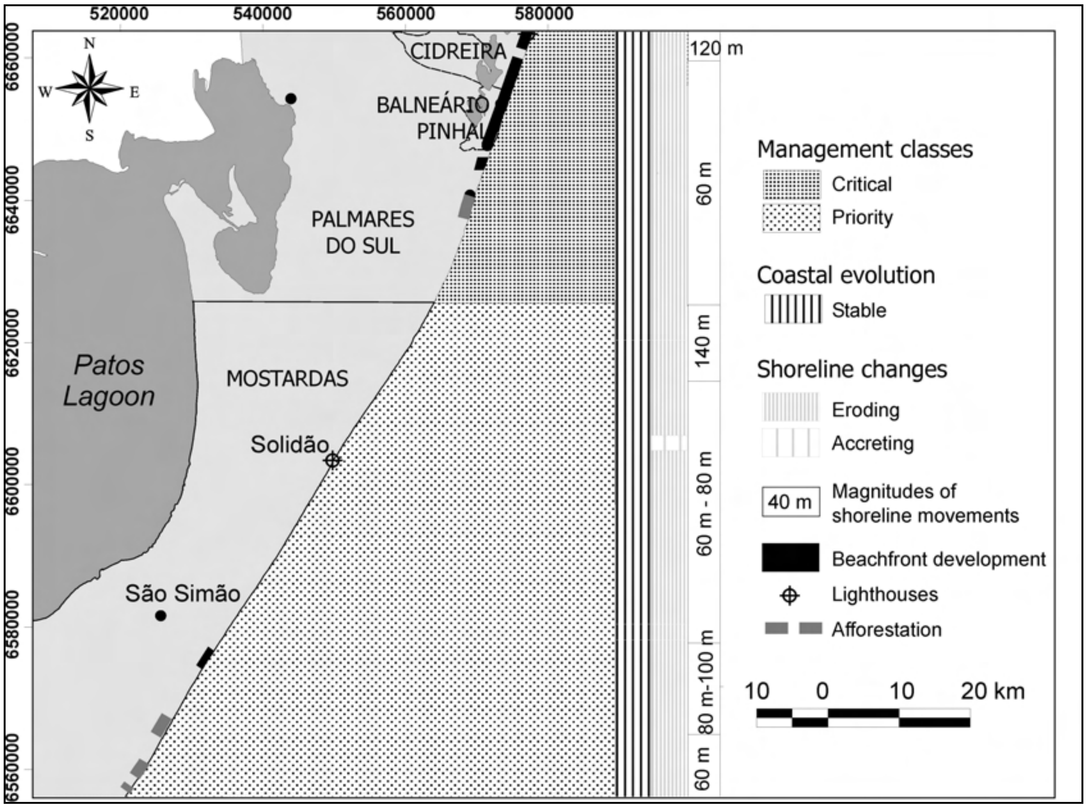

Figure 6.3. Beaches from Cidreira (northern coastal sector) to Palmares do Sul (central sector) are classified as areas of critical management, while beaches of Mostardas are classified as priority areas. Although these beaches are stable in the long term, they are mainly eroding in the short term.

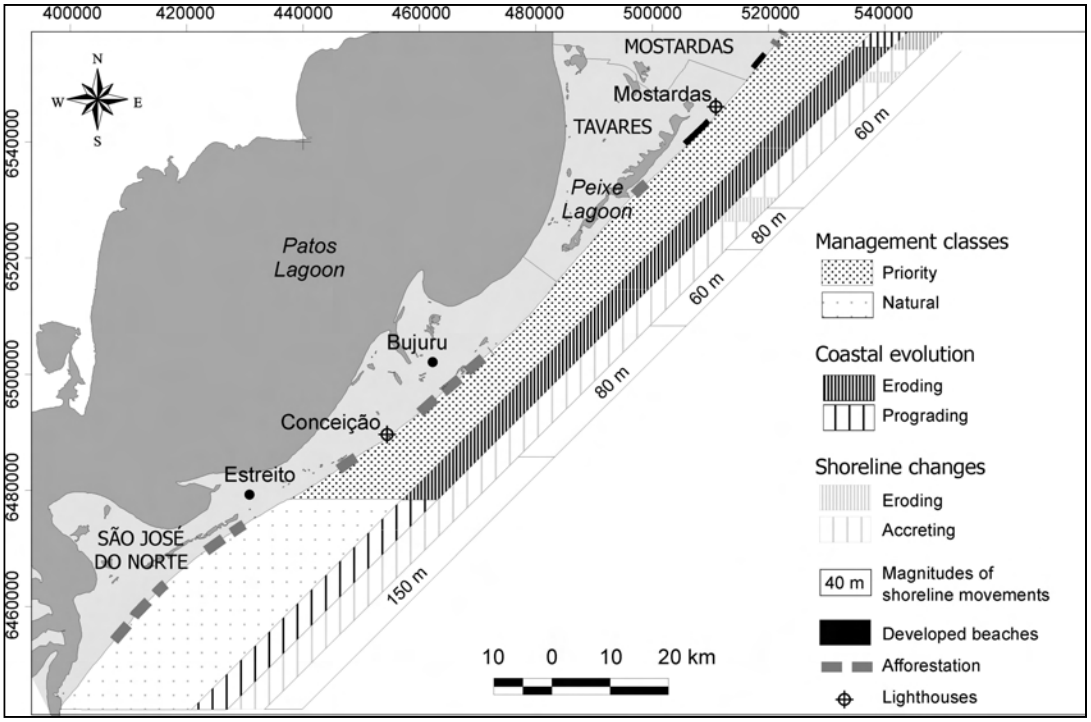

Figure 6.4. The shores from Mostardas to Estreito, in São José do Norte (central sector), are classified as priority areas as they are eroding in the long and/or in the short term. Beaches south of Estreito are accreting in the long and short terms and are classified as natural areas but the impacts of the jetties the afforestations on the local sediment budget and dynamics of the beach system should be better evaluated.

Southern Sector

In the southern segment, only 8 km or 3.6% of the shoreline length is developed (Table 6.2) concentrated mainly at the northernmost (Fig. 6.5) and southernmost ends (Fig. 6.6). In Santa Vitória do Palmar, developed beaches represent 2.3% of the shoreline length and occur from Barra do Chuí to Hermenegildo, where beachfront properties are built on top of the dunes (Esteves *et al.*, 2003a). In Cassino and Querência (Rio Grande), the well-developed dunes have shown a decrease in size and height partly because they were often cut to facilitate the access of vehicles to the beach and used as sand source for land fill or construction uses. Since 1986, projects of dune restoration have recovered the dunes along 2.5 km of the Cassino beach (NEMA, http://www.octopus.furg.br/nema/dunas/dunas.htm). Santa Vitória do Palmar and Rio Grande show rates of population growth lower than the state's average 0.72% and 0.89%, respectively (group III, Table 6.1). There are no signs of enhancing population growth or development along the southern sector in the near future as the access is difficult to great part of this shoreline and southern RS is one of the most undeveloped areas in the state. Possibly, the only change the southern coast may experience is related to the expansion of the Rio Grande Port, what can cause some impact in Cassino beach. The consequences of unplanned occupation are reflected by the destruction of coastal properties during storms in Hermenegildo, and by beach traffic and contamination of coastal waters in the summer in Cassino. The use of the undeveloped beaches in this segment is minor, showing some traffic along the beach and fishing activities (commercial boats and line fishing). The major human activity along this shoreline is the presence of *Pinus elliotis* afforestations located too close to the active dunes extending along about 64 km alongshore (Table 6.2).

From Rio Grande to Albardão lighthouse, beach accretion has dominated in the long and short terms (Fig. 6.5). South of Albardão, barrier retreat has been observed in the last 5 ka and alternating areas of erosion and accretion were registered from 1997 to 2002 (Fig. 6.6). The northernmost 15 km are classified as area of critical management (Fig. 6.5) due to the alteration in the natural conditions caused by human activities (*e.g.* beach traffic, jetties, destruction of dunes, pollution). A great part of the southern sector (about 124 km) is classified as natural areas as beaches are undeveloped, there is no evidence of increasing population or occupation, and there is a trend to accretion in the short and long terms (Fig. 6.5 and 6.6). However, further

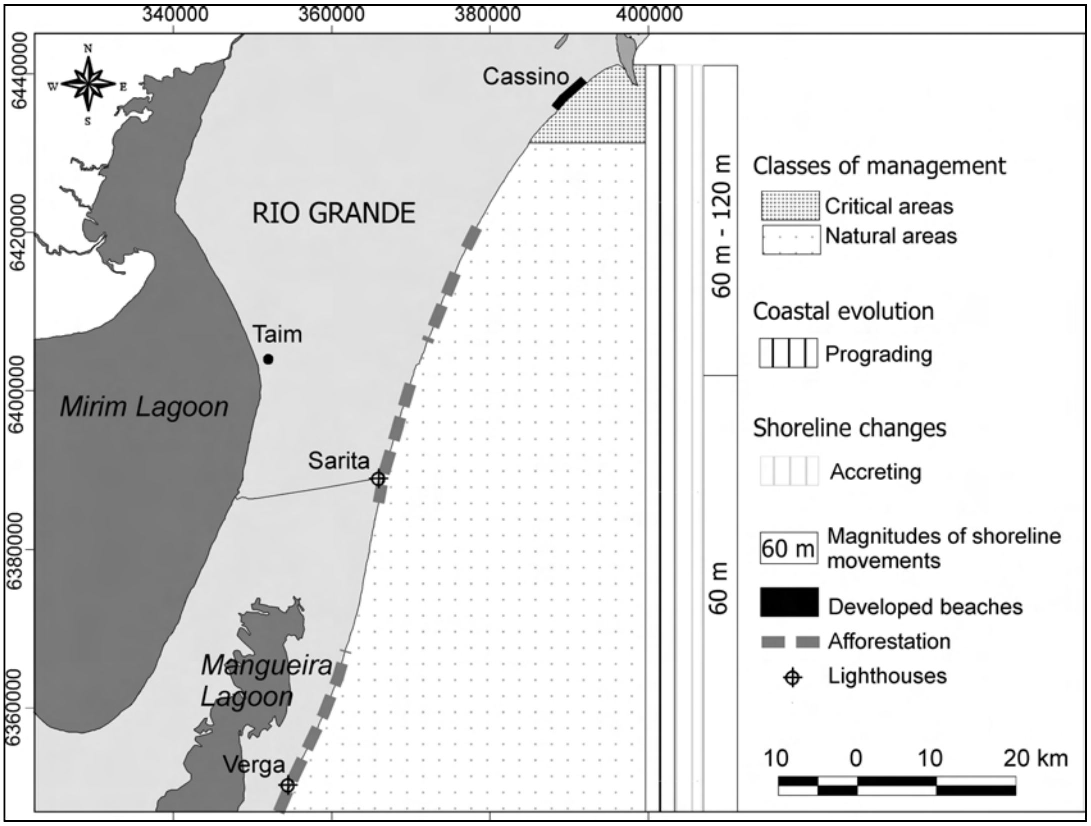

Figure 6.5. The northernmost 15 km of the Rio Grande coastline (southern sector) are classified as critical areas due to the alteration of the beach-dune system while other beaches are classified as natural areas. However, the impacts of afforestations too close to the dunes should be better evaluated to determine whether a setback line should be implemented for this activity.

studies are required to assess the potential impacts of the afforestation too close to the beach and to determine whether a setback line should be applied to this activity. The proximity of these beaches to the Taim Ecological Station support regulatory measures to restrict uses that would pose a threat to the preservation of the wetland. This could be implemented either by extending the preservation area to incorporate the beach or restricting uses to activities such as ecotourism, which are usually less damaging to the environment and could be taxed to provide financial resources to support management of the area. About 65 km of undeveloped beaches between Albardão and Hermenegildo are classified as areas of future concern (Fig. 6.6), where regulation should restrict occupation along eroded beaches. The southernmost 16 km are classified as critical areas (Fig. 6.6) due to the impacts of unplanned occupation adjacent to eroded shorelines, including undeveloped beaches where regulations of beach use and occupation should be implemented. Beach erosion has threatened Hermenegildo resulting in economic degradation due to costs of coastal protection, destruction of structures during storms, and depreciation of beachfront property values (Esteves & Santos, 2001). Although Barra do Chuí is located downdrift of a stabilized inlet, it is not experiencing significant erosion in the short term, probably due to the bidirectional character of the longshore currents (Nicolodi *et al.*, 2000; Esteves *et al.*, 2004a) and the short extension of the jetty.

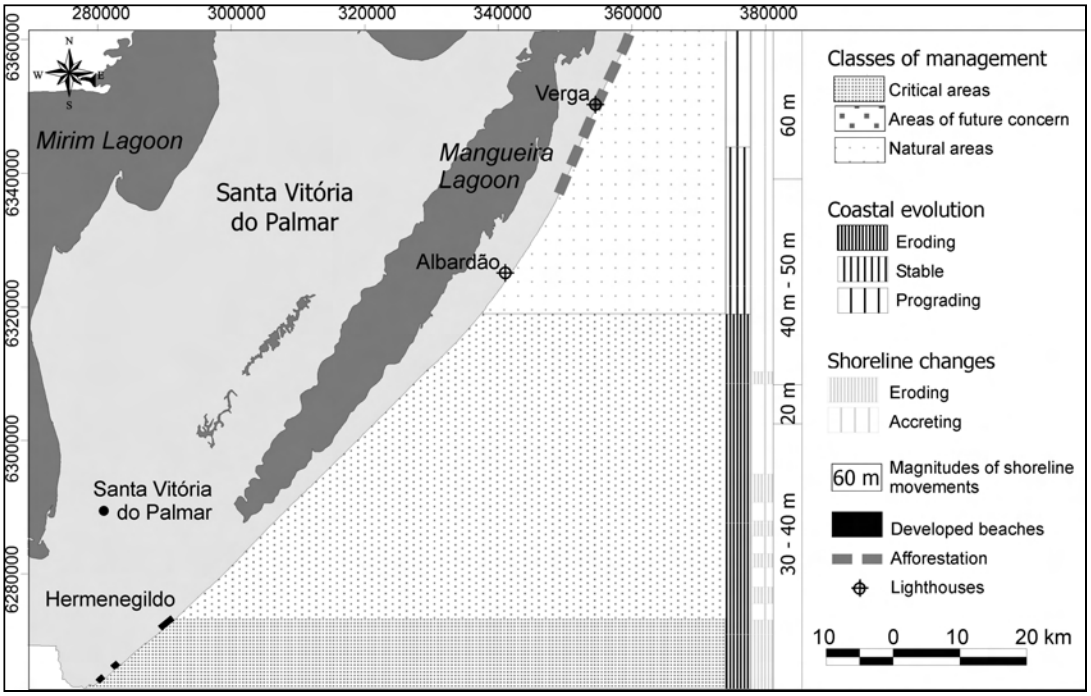

Figure 6.6. Along the shores of Santa Vitória do Palmar, the beaches from Verga to Albardão are classified as natural areas, from Albardão to Hermenegildo beaches are classified as areas of future concern, and from Hermenegildo to Chuí as areas of critical management.

DISCUSSION

According to Moraes (1995), occupation along the Brazilian coast is a recent process that is mainly unplanned and chaotic demanding major efforts in corrective management. The author emphasizes that the fragility of the coastal ecosystems and the pressure of accelerated development set priority for management plans in two areas: (a) in the surroundings of established urban centers, and (b) the creation of new development in pristine coasts. These two conditions are represented in RS especially by the northern coastal sector and the northern half of the central sector, respectively. Development is intense along the northern coastal sector and the consequences of unplanned occupation have been aggravated by the accelerated population growth in the last decade. As problems due to the increase in the demand for resources and space along the northern sector are exacerbated, tourists tend to escape to the nearest available area, i.e. the central sector. The central coastal sector has shown a recent trend of accelerating population growth and new developments are to be established in pristine areas. Although both areas need urgent implementation of management plans, the northern sector demands mainly corrective measures while the central sector requires preventive management. Preventive management is usually more effective, less expensive and easier to implement than corrective measures and tends to reduce critical areas in the future. However, preventive management is usually applied to areas where development is absent or incipient and natural conditions are still preserved. Fortunately, most of the RS coast fits in this category.

The FEPAM decided that the GERCO/RS should address first the northern sector because it is the most developed coastal area (FEPAM, 2000). The GERCO/RS defined 14 Ecologic and Economic Zones (ZEE) for the northern sector, presenting their characteristics, restrictions of uses, and activities to be promoted (FEPAM, 2000). As an example, it has been defined for the developed beaches that (a) foredunes should be preserved or restored, (b) a setback line for coastal constructions should be set 60 m inland of the foredunes baseline, and (c) recreation, tourism, and development should be promoted. There is no doubt that a management plan has to be established along intensely developed shorelines, the question here is whether the priority should be given to these areas. Considering that about 77% of this shoreline is developed, from which half the length represents constructions built on top of the dunes (Table 6.2), it seems to be less effective to establish control construction lines and dune preservation along the northern sector than along the mainly undeveloped central and southern sectors. Additionally, beaches along the northern sector are mainly accreting in the long and short terms while erosion is observed in areas where further (or new) development will mean an increase in the number and length of critical management areas with time. Defining the ZEE and establishing setback lines and restrictions of use along undeveloped areas under erosion or ecologically important areas appear to be the faster and most efficient way to reduce efforts of corrective management in the medium and long terms. Therefore, the importance of understanding shoreline changes in different time scales to help in the identification of the priority areas for coastal management.

About a decade ago, Tagliani (1995) has drawn attention for the need to define strategies for a planned development along the coastal sector on time to mitigate the environmental problems associated with unregulated occupation and uses. The author includes the present beach-dune system as conservation areas and lists the identification of erosion zones along the coast and lagoon margins amongst the most important aspects that need to be addressed to improve management in that sector. Thus, results presented in this study contribute towards a better understanding of some of the parameters that are important to define the best management practices for different sectors of the RS coast at a regional scale. The best management practices are defined also according to social, economic, and cultural issues that need to be evaluated at a local scale. Priority areas represent about one third of the RS coast and are concentrated in the central sector. The best alternative to these areas is to implement management policies to promote their natural characteristics. For example, the areas adjacent to the Lagoa do Peixe National Park show a great potential for ecotourism, an expanding activity that attracts half million tourists and generates R$ 500 million and 30,000 direct jobs per year in Brazil (MMA, http://www.mma.gov.br/port/sds/ecotur/corpo.html). Regulating occupation and uses along the central sector is crucial to preserve its natural resources. Critical areas represent 29% of the RS coast and include mainly developed beaches and their surroundings. The southernmost critical area comprises the beaches from Chuí to Hermenegildo, where development is not intense and is surrounded by long undeveloped shorelines. Thus, management strategies there should differ from the ones applied to the highly urbanized shores of the northern sector. For example, relocation or planned retreated should be evaluated as possible responses to the erosion problem in beaches such as Hermenegildo, where there is enough undeveloped area either alongshore or inland and beachfront properties are not worth an expensive protection measure. The same problem in the area of Tramandaí and Cidreira should be addressed in a different way as there is no room for relocation and tourism and beachfront properties represent significant economic revenue that needs to be protected.

CONCLUSIONS

This study points different classes of management for RS beaches based on the following factors: (a) rates of population growth from 1991 to 2000, (b) intensity of beachfront development and the state of conservation of the beach system, (c) shoreline change rates estimated for the period 1997 to 2002, and (d) coastal evolution in the Holocene. The RS beaches were classified into four classes of management: (1) areas of critical management occur along about 177 km or 29% of the RS coastal length, (2) priority areas are found along 198 km or 32% of the RS coastal length, (3) areas of future concern occur along 65 km or 10% of the coastal length, and (4) natural areas along 178 km or 29% of the RS coastal length.

Beaches along the northern coastal sector were classified as areas of critical management as they are highly developed (about 77% of the beachfront), show the highest rates of population growth (mean annual rate above 4%), and the beach-dune system is intensely altered. Beaches south of Xangrilá are eroding in the short term, demanding a management strategy different from the one designed for the accreted beaches to the north. Most of the central sector (198 km or 72%) is classified as priority areas, including the shores of Mostardas, Tavares, and the northern coastline of São José do Norte. About 23 km or 8.4% of the length of the central sector were classified as critical areas (Palmares do Sul), and 54 km or 19.6% of its length as natural areas (southernmost São José do Norte). Palmares do Sul and Mostardas show high rates of population growth (mean annual rate above 2%), but the first one was classified into the critical management class because it is located closer to the critical areas of the northern sector, is more intensely developed, and already shows problems due to unplanned occupation. The priority areas are mainly undeveloped with a preserved beach-dune system, show a potential of increasing pressure in the near future (due to recently facilitated access), and are eroding in the long or short term. Natural areas are pristine shores that are not threatened by population growth or accelerated development, and are mainly accreting. The southern coastal sector is dominated by natural areas (124 km or 56% of its length), although 65 km or 30% of its length are classified as areas of future concern (beaches from Hermenegildo to Albardão), and 31 km (14%) are classified as critical areas (from Chuí to Hermenegildo and Cassino).

It is discussed in this study that priority areas should be addressed first in a longer term state program of coastal management because preventive management is easier and less expensive to implement, and is more efficient as it reduces the number and length of critical areas in the medium to long terms. Additionally, data related to short-term shoreline changes and coastal evolution are presented and used to define classes of management. The identification of eroding beaches in the long or short terms is especially important because these areas need to be addressed more urgently than accreting beaches to prevent development in risk zones. Management measures applied for eroding areas need to include setback lines and restriction zones for development and uses.

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CAPÍTULO 7

CONCLUSÕES

Os monitoramentos da linha de costa realizados por DGPS mostram que a costa do RS tem 618 km de extensão. Com base em levantamentos de campo realizados em 2000 (Capítulo 2), a extensão do litoral do RS foi descrita como sendo de aproximadamente 630 km nos capítulos 2, 3 e 4 desta tese. Considerando-se que em nenhuma das cinco situações em que a linha de costa foi mapeada por DGPS este comprimento foi registrado e que a FEPAM utiliza o valor de 618 km, esta deve ser esta a extensão correta do litoral gaúcho. De acordo com a FEPAM (http://www.fepam.rs.gov.br/programas/gerco.asp), a costa do RS pode ser dividida em quatro setores: (1) o litoral norte, estendendo-se de Torres, no limite com o estado de Santa Catarina, até Balneário Pinhal, (2) o litoral médio leste, seguindo de Palmares do Sul até São José do Norte, (3) o litoral médio oeste, consistindo nos municípios ao longo da margem oeste da Lagoa dos Patos, e o (4) litoral sul, que compreende os municípios de Rio Grande e Santa Vitória do Palmar. Este estudo não abrange a costa lagunar, de forma que a costa oceânica dos 16 municípios costeiros do RS é aqui dividida em três setores seguindo-se a divisão estabelecida pela FEPAM: (1) o litoral norte, apresentando 123 km, (2) o litoral médio ou central, que se extende por 275 km, e (3) o litoral sul, com 220 km de extensão. Apesar de outros limites terem sido utilizados nos capítulos iniciais deste estudo, posteriormente passou-se a adotar esta divisão que parece ser a mais adequada no momento. Os resultados apresentados nos artigos que compõe esta tese possibilitam fazer uma descrição regional das condições atuais em que se encontra a costa do RS com base em parâmetros como: a ocupação urbana, crescimento populacional, nível de alteração antrópica das praias, variabilidade temporal e espacial das flutuações da linha de costa de curto termo, e as tendências de acresção, estabilidade ou erosão no longo termo. A análise integrada desses parâmetros permitiu ainda definir classes de manejo costeiro para diferentes setores da costa, identificando áreas que necessitam ser atendidas mais urgentemente por medidas preventivas ou corretivas (áreas prioritárias e críticas, respectivamente). As principais conclusões deste estudo são apresentadas a seguir.

O uso do DGPS cinemático para monitorar posições da linha de costa ao longo de toda a extensão do litoral do RS possibilitou comparar a dinâmica sazonal e interanual das flutuações da linha de costa em diferentes trechos do litoral gaúcho, em escala e detalhamento inéditos. Os resultados mostraram diferenças regionais na magnitude dos deslocamentos, no padrão sazonal dos deslocamentos e no intervalo de tempo em que a linha de costa retorna a sua configuração e posição antecedentes. No litoral sul, a linha de costa responde de maneira distinta ao sul e ao norte do Albardão, onde ocorre uma mudança significativa na orientação da linha de costa. Ao norte do Albardão, os deslocamentos anuais da linha de costa mostram sempre acresção, enquanto ao sul eles mostram acresção em um ano e erosão no ano seguinte. No litoral médio, as flutuações anuais da linha de costa apresentam um padrão ondulatório, no qual áreas em erosão ocorrem adjacentes a áreas em acresção e apresentam movimentos opostos em anos consecutivos. Os deslocamentos anuais no litoral norte também apresentam um comportamento ondulatório e antagônico semelhante ao do litoral médio. No entanto, no litoral norte, não há alternância entre áreas em erosão e acresção ao longo da costa, de forma que acresção praial domina em um ano e erosão domina no ano seguinte.

Um dos resultados mais intrigantes deste estudo refere-se ao retorno da linha de costa a uma posição anterior, formando uma imagem especular nos gráficos de deslocamento da linha de costa. Este processo foi verificado em um intervalo de sete meses entre Albardão e Cassino no litoral sul e dezenove meses no litoral norte, nos outros setores não foi observada uma imagem especular, embora a linha de costa tenha se deslocado para direções opostas. Este processo já foi observado na costa leste dos EUA comparando-se deslocamentos da linha de costa num período de duas semanas, antes e depois de uma tempestade (List & Farris, 1999). Como esta imagem especular foi observada para praias distintas em diversas escalas de tempo, provavelmente o retorno da linha de costa a sua forma e posição anteriores é uma questão de tempo. De forma que somente monitoramentos sistemáticos realizados por um longo período poderão mostrar se esta forma e posição anteriores são dominantes no tempo ou apenas momentos transitórios entre estados altamente dinâmicos.

Os resultados apresentados aqui corroboram com estudos anteriores que mostram as variações sazonais no perfil praial, que tende a erodir nos meses de outono e inverno, decorrente da maior energia de ondas e maior freqüência das tempestades, e a engordar durante os meses de primavera e verão. O comportamento antagônico dos deslocamentos anuais da linha de costa coincide com os eventos de El Niño e La Niña que ocorreram em 1997-1998 e 1999, respectivamente. Os efeitos do El Niño na dinâmica costeira provavelmente foram os responsáveis pela retração da linha de costa registrada em novembro de 1997. O período pós-El Niño caracterizado pela redução na energia dos ventos e ondas possibilitou a recuperação da praia, resultando na acresção observada entre novembro de 1997 e novembro de 1998. Já o aumento da ciclogênese durante o evento La Niña de 1999 resultou na retração da linha de costa observada entre novembro de 1998 e novembro de 1999. Esta variabilidade temporal dos deslocamentos anuais no litoral médio e norte faz com que estimativas de taxas de variação da linha de costa possam apresentar valores muito distintos e até opostos dependendo do intervalo de tempo analisado. Taxas estimadas com base na comparação de posições da linha de costa obtidas em apenas duas datas são particularmente sensíveis e devem ser consideradas apenas quando as condições (oceanográficas e meteorológicas) que os dados representam forem conhecidas. Esta grande variabilidade temporal e espacial nos deslocamentos da linha de costa é responsável pela diferença nos resultados obtidos por estudos que analisam mudanças na morfologia costeira em diferentes escalas de tempo.

A variabilidade espacial na resposta da linha de costa às mudanças sazonais e interanuais deve-se a uma combinação de fatores de modo que é difícil determinar qual é o mais importante. As maiores variações da linha de costa ocorrem em embaiamentos e estão associadas a tamanhos de grão menores. Leves mudanças na orientação da linha de costa coincidem com variações na granulometria dos sedimentos praiais e com o padrão ondulatório dos deslocamentos anuais da linha de costa, que também estão relacionados com os gradientes no transporte sedimentar longitudinal mostrados pelos modelos. Os maiores volumes de transporte foram observados ao longo das praias mais expostas às ondas de SSW (geralmente associadas à passagem de frentes frias), que são áreas dominadas por erosão (*i.e.* ao sul do Albardão e entre o Estreito e o farol da Conceição). A alternância entre áreas de erosão e acresção no litoral médio pode ser causada por ondas que se aproximam da costa em ângulos maiores do que o de máximo transporte de sedimento conforme descrito por Ashton *et al.* (2003) e Murray & Ashton (2003). Os resultados referentes ao transporte de sedimento são baseados em modelos matemáticos e só poderão ser validados quando medições de ondas e correntes ao longo da costa do Rio Grande do Sul estiverem disponíveis. A falta de dados de ondas, correntes e transporte sedimentar é um fator limitante para a verificação e quantificação das relações entre as mudanças nas condições energéticas ao longo da costa e ao longo do tempo e as respostas da linha de costa.

Apenas 123 km ou aproximadamente 20% da costa do RS encontram-se urbanizados, concentrados principalmente no litoral norte, onde a ocupação desordenada, o uso intensivo e o crescimento populacional acelerado resultaram em um sistema praial dominantemente alterado. Mesmo nas áreas menos urbanizadas (litoral central e sul), a ocupação urbana é sempre caracterizada pela falta de planejamento, ocupação de áreas de risco, destruição ou alteração de áreas protegidas por lei, e/ou interferência nos processos dinâmicos naturais. Características que parecem ser típicas da ocupação costeira no Brasil (Moraes, 1995). Como resultado, quase um terço (32%) do litoral gaúcho apresenta-se alterado por atividades antrópicas. O aumento acelerado da população costeira não só agrava os problemas existentes como tende a extendê-los sobre áreas adjacentes. Embora o RS apresente uma densidade populacional na costa menor do que a média do estado, sete dos dez municípios de maior crescimento populacional entre 1991 e 2000 localizam-se no litoral norte. O aumento da demanda por espaço e o crescimento populacional já são observados também em Palmares do Sul e Mostardas, municípios do litoral médio. Estes dois municípios localizam-se mais próximos das áreas mais populosas do estado e recentemente tiveram acesso facilitado através do asfaltamento da BR101.

Considerando-se apenas as variáveis relacionadas ao crescimento populacional, ocupação urbana e impactos antrópicos, o litoral norte e as praias urbanizadas de Palmares do Sul já são classificados como áreas de manejo crítico, que requerem medidas corretivas. As áreas urbanizadas do litoral sul (praia do Cassino, Hermenegildo e Chuí) também são enquadradas nessa mesma categoria. Já os trechos da costa de Palmares do Sul e Mostardas que atualmente são pouco ocupados, mas que apresentam uma tendência recente de intensificação de seu uso (taxas de crescimento populacional acima da média do estado e acesso facilitado), são classificados como áreas prioritárias de gerenciamento costeiro, que necessitam urgentemente de medidas que regulamentem a ocupação e usos. As demais áreas da costa do RS apresentam pouca ou nenhuma pressão de ocupação urbana e não há indícios de que este cenário seja modificado nos próximos anos, sendo então classificadas como áreas em que a implementação de planos de manejo são menos urgentes. O gerenciamento costeiro integrado visa o desenvolvimento sustentável através da harmonização entre as atividades antrópicas e o ambiente físico. Estabelecer tendências e quantificar a magnitude das flutuações da linha de costa, tanto em eventos extremos quanto em taxas médias ao longo do tempo, é essencial para definir classes de manejo em áreas pouco ocupadas e estabelecer as estratégias mais adequadas em áreas urbanizadas. Sendo assim, enquanto a evolução costeira de longo termo (centenas a milhares de anos) define tendências de acresção ou erosão, as variações de curto termo (sazonais e interanuais) são fundamentais para identificar áreas de risco em escalas de tempo compatíveis com planos de manejo. As variações extremas na posição da linha de costa são particularmente importantes em costas sujeitas à alta energia de onda, onde tempestades intensas e eventos como El Niño geram retração costeira e destruição de estruturas, conforme demonstrado por Allan *et al.* (2003) para a costa do Oregon, nos EUA. Os autores mostram que, enquanto determinado setor da costa pode estar estável ou em acreção em uma escala de centenas de anos, o impacto de eventos de alta energia pode resultar em períodos de erosão acelerada que pode perdurar por meses ou anos, culminando na destruição de construções costeiras. Portanto, linhas de recuo para construções costeiras devem ser baseadas nessas flutuações de curto termo, pois são elas que ameaçam a integridade de estruturas, colocam a população em risco e trazem prejuízos econômicos às comunidades costeiras.

No Rio Grande do Sul, por exemplo, durante o Holoceno, barreiras progradantes dominam a costa entre Torres e Tramandaí e barreiras estáveis dominam entre Tramandaí e Mostardas. No entanto, erosão tem sido dominante nas praias ao sul de Xangrilá até Mostardas, no curto e médio prazos. Nessas áreas, a variabilidade na posição da linha de costa em escalas de anos a décadas aumenta os riscos de inundação e destruição de estruturas, impondo que sejam definidas estratégias de manejo para áreas em erosão, como linhas de recuo para construções, restrição de usos e relocação de estruturas ou atividades ameaçadas, mesmo que a costa esteja progradando no longo termo. Já entre Mostardas e Estreito, a retração costeira dominou durante o Holoceno enquanto, no curto termo, as grandes magnitudes e a variabilidade temporal e espacial dos deslocamentos da linha de costa fazem com que erosão ou acresção sejam registradas dependendo do período de tempo analisado. Essas praias são muito suscetíveis às flutuações da linha de costa o que as torna inadequadas para ocupação urbana. Desta forma, mesmo que essas áreas atualmente se encontrem desocupadas e sem demanda de uso, são consideradas prioritárias para o gerenciamento costeiro. O trecho de costa não urbanizado entre o Chuí e o Hermenegildo, apresenta tendência à erosão no longo e curto termo e proximidade com áreas críticas, de forma que também é incluído nesta categoria. As praias entre o Hermenegildo e o Albardão atualmente não apresentam nenhuma pressão de uso ou ocupação, mas por apresentarem tendência à erosão em diferentes escalas de tempo, são classificadas como áreas latentes.

Além das características antrópicas e da dinâmica costeira, a presença de ecossistemas ecologicamente sensíveis ou protegidos pela legislação ambiental, também deve ser considerada nos planos de manejo. A proximidade dessas áreas é um atrativo para o ecoturismo que é um dos setores de maior crescimento da indústria do turismo e que, no Brasil, gera R$ 500 milhões e 30 mil empregos diretos por ano (http://www.mma.gov.br/port/sds/ecotur/corpo.htm). Embora o ecoturismo tenha na conservação do ambiente natural o seu fundamento, também pode gerar a sua degradação se a intensificação do uso não for controlada. A presença de atrativos naturais aliada à facilidade de acesso e à falta de regulamentação geralmente resulta na sobre-exploração e degradação ambiental (Page, 1998). Esta deve ser mais uma preocupação ao longo do litoral central onde se localiza o Parque Nacional da Lagoa do Peixe. Considerando todos os fatores discutidos acima, este estudo classifica a costa do Rio Grande do Sul em quatro classes de manejo distribuídas da seguinte forma: (1) *áreas de manejo crítico*, ocorrem em 177 km ou 29% da costa do RS e consistem basicamente nas áreas urbanizadas, concentradas principalmente no litoral norte, (2) *áreas prioritárias*, ocorrem em 198 km ao longo do litoral médio, ocupando 32% da costa do RS, (3) *áreas latentes* ocorrem em 65 km ou 10% da costa, localizados no litoral sul entre o Hermenegildo e o Albardão e (4) *áreas naturais*, ao longo de 178 km ou 29% da costa gaúcha, encontradas no litoral central e sul.

CAPÍTULO 8

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