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CURSO DE MESTRADO EM ECOLOGIA DE ECOSSISTEMAS COSTEIROS E ESTUARINOS

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CONDIÇÕES OCEANOGRÁFICAS, OCUPAÇÃO TERRITORIAL E PROBLEMAS AMBIENTAIS NA PRAIA DO ATALAIA (NORDESTE DO PARÁ, BRASIL)

BRAGANÇA-PA

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Dissertação apresentada ao Programa de Pós-graduação em Biologia Ambiental, Mestrado em Ecologia de Ecossistemas Costeiros e Estuarinos da Universidade Federal do Pará, Campus de Bragança, como um dos requisitos necessários à obtenção do título de Mestre em Biologia Ambiental**.**

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RESUMO

A conservação e gestão da zona costeira da região amazônica merecem atenção especial, devido à riqueza de seus recursos naturais. O presente estudo visa avaliar os impactos dos eventos naturais e atividades humanas na praia de Atalaia, situada no estado do Pará (Brasil), e o desenvolvimento de diretrizes para a implementação de programas de gestão costeira. Os dados foram coletados entre novembro/2008 e novembro/2010. Quatro conjuntos de variáveis foram avaliados: (i) variáveis físicas (climatologia, hidrodinâmica e morfodinâmica), (ii) variáveis hidrológicas (temperatura da água, salinidade, pH, turbidez, oxigênio dissolvido e nutrientes inorgânicos dissolvidos, clorofila *a* e níveis de coliformes termotolerantes), (iii) desenvolvimento urbano e (iv) distribuição espacial de serviços e infraestrutura. Os resultados indicam que o clima e as condições hidrodinâmicas foram os principais fatores responsáveis pelas flutuações na qualidade de água, turbidez, oxigênio dissolvido, nutrientes inorgânicos dissolvidos e concentrações de clorofila *a*. A descarga de esgoto doméstico não tratado foi responsável pela contaminação bacteriológica, embora a rápida turbulência decorrente da alta energia hidrodinâmica do ambiente tenha limitado a contaminação por coliformes termotolerantes. Esta alta energia hidrodinâmica, principalmente durante as marés equinociais de sizígia e a falta de planejamento urbano gera outros problemas, tais como a erosão costeira. A área de estudo é caracterizada por altas taxas pluviométricas (> 1900 mm durante a estação chuvosa), ventos de NE com velocidades médias mensais superiores a 4,36 m/s na estação seca e 3,06 m/s na estação chuvosa, condições de macromaré (alcance da maré > 4,0 m), velocidades moderadas de correntes de maré (superior a 0,5 m/s) e alturas de ondas significantes superior a 1,5 m. Em março e junho (meses chuvosos), a corrente de maré vazante alcançou um máximo de 0,4 m/s. O ciclo de maré foi fracamente assimétrico com a maré vazante durando mais de 6 horas e 40 minutos. A energia das ondas foram fracamente moduladas pela maré baixa devido à atenuação das ondas em bancos de areia. A temperatura da água foi relativamente homogênea (27,4°C a 29,3°C). A salinidade variou de 5,7 (junho) a 37,4 (novembro). A água foi bem oxigenada (superior a 9,17 mg/L), turva (superior a 118 NTU), alcalina (acima de 8,68) e eutrófica (máximo de 2,36 µmol/L para nitrito, 24,34 µmol/L para nitrato, 0,6 µmol/L para fosfato e 329,7 µmol/L para silicato), além de apresentar altas concentrações de clorofila *a* (acima de 82 mg/m³). As condições naturais observadas no presente estudo indicam a necessidade de uma revisão dos critérios hidrológicos usados para avaliação de praias por agências nacionais e internacionais e sua adaptação para a realidade da costa amazônica. A falta de sistema de saneamento público levou a contaminação bacteriológica e a perda da qualidade da água. Com relação ao estado morfodinâmico, as condições dissipativas foram encontradas durante alta a moderada energia hidrodinâmica (condições equinociais e não-equinociais), porém em novembro as maiores alturas de ondas geraram características de *barred dissipative*, enquanto nos outros meses características *non-barred* foram dominantes. Desta forma, o modelo proposto por Masselink & Short (1993) parece não ser ideal para ser aplicado em praias com características similares a praia de Atalaia, na qual a energia das ondas é modulada pela presença de bancos de areia durante algumas fases da maré.

PALAVRAS-CHAVE: climatologia, hidrologia, hidrodinâmica, morfodinâmica e uso e ocupação.

ABSTRACT

The conservation and management of the coastal zone of the Amazon region demands special attention, given the richness of its natural resources. The aim of the present study was to evaluate the impact of natural events and human activities on Atalaia beach, situated in the NE of the Brazilian state of Pará and to develop guidelines for the implementation of coastal management programs. Data were collected between November, 2008, and November, 2010. Four sets of variables were assessed: (i) physical variables (climatology, hydrodynamics and morfodinâmica), (ii) hydrological variables (water temperature, salinity, pH, turbidity, dissolved oxygen and inorganics nutrients, chlorophyll *a* and thermotolerant coliform levels), (iii) urban development and (iv) spatial distribution of services and infrastructure. The results indicate that climate and hydrodynamical conditions were the main factors responsible for fluctuations in water salinity, turbidity, dissolved oxygen, inorganic dissolved nutrients, and chlorophyll *a* concentrations. The discharge of untreated domestic sewage was responsible for bacteriological contamination, although the rapid turnover of the high-energy hydrodynamic environment limited contamination by thermotolerant coliforms. This high hydrodynamic energy, primarily during the equinoctial spring tides, and the lack of urban planning, nevertheless generates other problems, such as coastal erosion. The study area is characterized by high rainfall rates (> 1900 mm during the rainy season), NE winds with mean speeds of up to 4.36 m/s in the dry season and 3.06 m/s in rainy season, macrotidal conditions (tidal range > 4.0 m), moderate tidal current speeds (up to 0.5 m/s), and significant wave heights up to 1.5 m. In March and June (rainiest months), ebb tide currents reached a maximal of 0.4 m/s. Tidal cycle was weakly asymmetric with the ebb tide lasting up to 6 hours 40 minutes. Wave energy was slightly modulated by the low tide due to wave attenuation on sand banks. Water temperature was relatively homogeneous (27.4ºC to 29.3ºC). Salinity varied from 5.7 (June) to 37.4 (November). The water was well oxygenated (up to 9.17 mg/L), turbid (up to 118 nephelometric turbidity units), alkaline (up to 8.68), and eutrophic (maximum of 2.36 µmol/L for nitrite, 24.34 µmol/L for nitrate, 0.6 µmol/L for phosphate, and 329.7 µmol/L for silicate), and it presented high concentrations of chlorophyll *a* (up to 82 mg/m^3). The natural conditions observed in the present study indicate the need for a review of the hydrologic criteria used for the evaluation of beaches by national and international agencies and their adaptation to the reality of the Amazon Coast. The lack of a public sanitation system has led to bacteriologic contamination and the loss of water quality. With respect to morphodynamic state, dissipative conditions were found during high and moderate hydrodynamic energy (equinoctial and non-equinoctial condition), but in November the highest wave heights generated barred dissipative characteristic, whereas during the other months non-barred characteristics dominated. Thus, this study shows that the model proposed by Masselink & Short (1993) seems to be ideal to be applied to beaches with similar characteristics to the studied beach, where wave energy is modulated by the presence of sand banks in some stages of the tide.

Kewords: climatology, hydrology, hydrodynamic, morphodynamic, use and occupation.

ESTRUTURA DA DISSERTAÇÃO

Esta dissertação foi elaborada em formato de artigo, segundo as normas do Programa de Pós-graduação em Biologia Ambiental da Universidade Federal do Pará.

O trabalho foi estruturado em cinco capítulos:

- Capítulo I: contém a Introdução Geral apresentando as características dos diversos ecossistemas costeiros, bem como do litoral brasileiro ressaltando o Litoral Amazônico. Os diferentes parâmetros analisados durante a pesquisa, tais como: hidrodinâmica, morfodinâmica, sedimentologia, hidrologia, climatologia e processos de ocupação na zona costeira são apresentados neste capítulo.

- Capítulo II: contém o artigo publicado no *Journal of Coastal Research* (JCR) 2011 e tem como título: "***Effects of The Lack of Coastal Planning on Water Quality and Land Use on a Macrotidal Beach (Atalaia, Pará) in the Amazon Region".*** O mesmo retrata os impactos das atividades humanas nas características naturais da praia, além de apresentar diretrizes para a implementação de programas de gestão costeira.

- Capítulo III: contém o artigo aceito na revista *Journal of Coastal Research* e tem como título "***Oceanographic Conditions and Human Factors on the Water Quality at an Amazon Macrotidal Beach"***. Este capítulo aborda os efeitos das variações sazonais nas condições meteorológicas, hidrodinâmicas, hidrológicas e microbiológicas e descreve as implicações da falta de sistema de saneamento público nas condições da qualidade da água utilizada para as atividades recreacionais, bem como a falta de infraestrutura e serviços.

- Capítulo IV: descreve as variações morfológicas em diferentes condições, como: períodos sazonais (seco e chuvoso) e marés equinociais de sizígia (Março e Setembro/09). O Estado morfodinâmico de Atalaia é analisado em quatro condições: *nearshore*, *offshore* e durante as fases de enchente e vazante da maré. Este artigo está em fase de preparação.

- Capítulo V: aborda as conclusões gerais da dissertação de forma integradora.

Em anexo estão a primeira página do artigo publicado e do artigo aceito para publicação, ambos no *Jornal of Coastal Research*.

CAPÍTULO I

1. INTRODUÇÃO GERAL

As áreas costeiras constituem aproximadamente 20% da área superficial das terras emersas do planeta, dos quais habitam cerca de 60% da população mundial (Tagliani *et al*., 2003). Estas áreas são altamente produtivas e diversas e possuem elevado valor ecológico e econômico, nas quais as populações humanas se beneficiam de seus recursos naturais e da ocupação de seu território (Beatley *et al*., 2002; Belfiore, 2003).

Nestas regiões podem ser encontrados diferentes ambientes deposicionais, como: planícies de marés, deltas, praias, dunas, estuários, lagoas, etc. que são vulneráveis as modificações antrópicas e naturais (Belfiore, 2003). Entretanto, nas últimas décadas, o elevado crescimento populacional associado às inúmeras atividades econômicas desenvolvidas sem planejamento adequado está gerando sérios problemas sócio-ambientais em diversas áreas costeiras ao longo do planeta (Small & Nicholls, 2003; Lau, 2005; Steffy & Kilkam, 2006).

Os ambientes deposicionais são imprescindíveis para a proteção costeira, ao mesmo tempo em que despertam um enorme interesse para diversos setores econômicos. Dentre os setores econômicos que atuam nestes ambientes estão: o setor imobiliário, comercial, turístico, pesqueiro, portuário, entre outros, que vêm gerando renda e atraindo populações que contribuem para as inúmeras transformações tanto ambientais, quanto sociais (Cicin-Sain & Knecht, 1998; Linton & Warner, 2003; Burak, 2004; Chen *et al*., 2005; Irtem *et al*., 2005; Ten Voorde *et al*., 2009). Atividades humanas podem comprometer a integridade desses ambientes, alterando a dinâmica natural do sistema e gerando problemas relacionados à contaminação das águas costeiras, erosão marinha, redução da biodiversidade, além de causarem riscos à saúde pública (Breton *et al*., 1996; Bartlett *et al*., 2000; Pereira *et al*., 2007; Crawford, 2007). Em adição, estes ambientes estão sujeitos a contínuas alterações morfodinâmicas moduladas por processos continentais e marinhos decorrentes de vários fatores de origem natural e antrópica, como por exemplo, oscilação do nível do mar, condições oceanográficas, climatológicas, ocupação desordenada e uso inadequado dos recursos naturais (Cambers, 1997; Micallef & Williams, 2002; Pereira *et al*., 2007).

Nas últimas décadas, o interesse no estudo da morfologia costeira tem aumentado, principalmente devido aos problemas de erosão/acresção que tem se agravado na maioria dos ambientes costeiros que apresentam interferências humanas (Wright *et al*., 1982; Jiménez *et al*., 1997; Kroon & Masselink, 2002 ; Battiau-Queney *et al*., 2003*;* Stépanian & Levoy, 2003). Os problemas erosivos têm recebido destaque por reduzir o perfil de praia e causar a destruição de edificações (Toldo *et al*., 1993; Pereira *et al*., 2000). Estes problemas quando associados à falta de serviços e infraestrutura ao longo das zonas costeiras estão comprometendo os ambientes naturais, afetando as condições requeridas pela população para desfrutar das áreas recreacionais, bem como o turismo (Pereira *et al*., 2003).

O Brasil ocupa uma grande área da América do Sul, cerca de 47% (Glaser & Diele, 2004) e possui uma linha de costa de, aproximadamente, 8.500 km de extensão, onde estão inseridos os mais variados ambientes costeiros equatoriais, tropicais e subtropicais (Diegues, 1999). Nesta região estão localizados 63% dos estados brasileiros, onde habitam quase um quarto do total da população do país (Szlafsztein, 2005).

Similarmente a outros países com extensa área costeira, o Brasil apresenta um grande potencial para o desenvolvimento de inúmeras atividades econômicas e, consequentemente, a falta de planejamento e o rápido processo de urbanização têm resultado em sérios processos de degradação sócio-ambiental, principalmente nos grandes centros urbanos.

Algumas áreas costeiras do Brasil são escassamente habitadas e possuem ecossistemas bem preservados de grande valor ambiental, mas que, no entanto, estão se tornando foco da ocupação humana e consequentemente alvo de impactos ambientais, como a costa amazônica (Szlafsztein, 2005).

A zona costeira amazônica ainda possui características singulares e, relativamente, bem preservadas em relação às outras regiões costeiras do país. Esta zona abrange os estados do Amapá, Pará e Maranhão e ocupa 35% da costa nacional, estendendo-se por mais de 2.500 km, desde a foz do Rio Oiapoque (Amapá) até a Baía de São Marcus, no Maranhão (Isaac & Barthem, 1995; Souza Filho *et al*., 2005). Nesta zona estão inseridas, cerca de, 85% dos manguezais do país (Lara, 2003), constituindo as maiores faixas contínuas de manguezais do mundo (Kjerfve *et al*., 2002) e que abrangem uma área de 10,713 km² (Schaeffer-Novelli, 1990; Vannucci, 1999; Lara, 2003).

A ocupação territorial sem planejamento, o acelerado crescimento populacional e a exploração ilegal dos recursos naturais são responsáveis por muitos conflitos ambientais e sociais que afetam os ecossistemas costeiros amazônicos (Krause & Glaser, 2003; Pereira *et al*., 2007).

O Estado do Pará (Norte do Brasil) ocupa 1.248.042 km² e representa 16.66% do território brasileiro e 26% da Amazônia Legal, onde vivem cerca de 48% da população da Região Norte. A zona costeira paraense corresponde a 7,3% do território estadual ocupado por

43% da população paraense, ou seja, cerca de 2.665.740 habitantes, vivendo em 40 municípios (IBGE, 2003). A mesma apresenta configuração morfológica extremamente recortada, feições geomorfológicas peculiares com extensos depósitos de planícies de maré, estuários, manguezais, baixios, pântanos salinos, dunas, praias e leques de lavagens associados (Souza Filho & El-Robrini, 1996) que recebem a influência da descarga do Rio Amazonas e de dezena de outros estuários.

As praias desta região apresentam uma dinâmica bastante diferente quando comparadas às demais praias situadas em outras regiões do Brasil, em decorrência, principalmente, do elevado aporte de águas continentais, dos regimes de macromarés semidiurnas, do grande aporte de partículas e de sedimentos, da incidência de fortes ventos alísios de nordeste e das elevadas taxas de precipitação pluviométrica (Geyer *et al.*, 1996; Meade *et al.*, 1985; Figueroa & Nobre, 1990; Marengo, 1995). Tais condições, somadas à extensa plataforma continental com baixa declividade, força de Coriolis reduzida, praticamente à zero, e a ocorrência de marés equinociais de sizígia (Nittrouer & Demaster, 1986; Marengo, 1995, Kineke *et al.*, 1996, Lam-Hoai *et al.*, 2006, Santos *et al.*, 2008, Silva *et al.*, 2009), controlam os padrões hidrológicos, hidrodinâmicos, sedimentológicos e morfodinâmicos ao longo desta costa.

Em virtude de sua extensão, este litoral foi dividido, segundo o Plano Estadual de Gestão da Zona Costeira (PNGZC), em três setores com diferentes aspectos geomorfológicos:

- Setor I – Setor costa Atlântica do "Salgado Paraense";
- Setor II – Setor Continental Estuarino;
- Setor III – Setor Insular Estuarino;

O Setor Costa Atlântica do Salgado Paraense é um dos mais povoados (Setor I), concentrando 27% da população do estado (Souza Filho, 2000; Pereira *et al.*, 2007), distribuídas em 22 municípios com uma área de 16.215 km² (19,5%) da área total da zona costeira paraense (Szlafsztein, 2005), sendo o mais afetado pela degradação ambiental (Szlafsztein, 2009; Gorayeb *et al.*, 2009; Guimarães *et al.*, 2009).

Por esta razão, visando planejar e realizar a gestão das atividades socioeconômicas que controlam, conservam e recuperam os recursos naturais que afetam ou podem afetar a zona costeira, o Estado do Pará estabeleceu na sua política ambiental (Lei Estadual n.º 5587/95), um grupo de objetivos, instrumentos e diretrizes para preservar e proteger o ambiente natural, e melhorar a qualidade de vida da população, em harmonia com o desenvolvimento socioeconômico sustentável, mas que, de forma alarmante, tem mostrado esforços quase nulos na implementação do programa de gestão costeira (GERCO/PA) (Szlafsztain, 2009).

Embora alguns estudos retratem a dinâmica da costa paraense, pouco se conhece a respeito da dinâmica costeira local, uma vez que a maioria das publicações científicas foram realizadas próximas ao Rio Amazonas (Nittrouer & DeMaster, 1986; DeMaster *et al.*, 1996; Santos *et al.*, 2008). Por tais razões, a Praia de Atalaia, situada na planície costeira de Salinópolis foi escolhida como estudo de caso deste trabalho por ser considerada o mais importante centro turístico costeiro do Estado do Pará.

Nesta praia, os processos oceanográficos naturais, as inúmeras atividades humanas associadas à falta de planejamento na ocupação territorial, principalmente em zonas de intermarés, dunas e falésias ativas têm acelerado os processos erosivos neste ambiente. Em adição, despejos inadequados de esgotos domésticos, presença de fossas sépticas ativas e inativas no ambiente de praia vem afetando a qualidade da água costeira, podendo colocar em risco a saúde dos usuários. A ocupação irregular e a falta de infraestrutura e serviços estão acelerando os problemas ambientais em Atalaia, principalmente, no período de férias escolares, onde a praia fica densamente ocupada por veranistas.

1.1 Objetivos Gerais

Conhecer as condições naturais e os principais problemas relacionados à contaminação da praia por ação antrópica, decorrente da falta de saneamento básico, além de identificar e quantificar as áreas propícias aos processos erosivos e acrescivos. Com base nestes resultados, medidas de gestão foram sugeridas para melhorar a qualidade da praia estudada.

1.2 Objetivos Específicos

- Determinar os efeitos das flutuações sazonais das condições meteorológicas e hidrodinâmicas, bem como as atividades humanas sobre as variáveis hidrológicas e microbiológicas (coliformes termotolerantes).

- Avaliar a influência dos aspectos meteorológicos e hidrodinâmicos no estado morfodinâmico e balanço sedimentar da praia de Atalaia, em diferentes períodos sazonais (seco e chuvoso).

- Propor medidas de gestão costeira para que futuros trabalhos de gestão sejam elaborados pelas autoridades competentes.

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CAPÍTULO II

2. EFFECTS OF THE LACK OF COASTAL PLANNING ON WATER QUALITY AND LAND USE ON A MACROTIDAL BEACH (ATALAIA, PARÁ) IN THE AMAZON REGION*

2.1 Abstract

The conservation and management of the coastal zone of the Amazon region demands special attention, given the richness of its natural resources. The aim of the present study was to evaluate the impact of natural events and human activities on Atalaia beach, and to develop guidelines for the implementation of coastal management programs. Data were collected between November, 2008, and November, 2010. Four sets of variables were assessed: (i) physical variables (climatology and hydrodynamics), (ii) hydrological variables (water temperature, salinity, pH, turbidity, dissolved oxygen and inorganics nutrients, chlorophyll *a* and thermotolerant coliform levels), (iii) urban development and (iv) spatial distribution of services and infrastructure. The results indicate that climate and hydrodynamical conditions were the main factors responsible for fluctuations in water salinity, turbidity, dissolved oxygen, dissolved nutrients, and chlorophyll *a* concentrations. The discharge of untreated domestic sewage was responsible for bacteriological contamination, although the rapid turnover of the high-energy hydrodynamic environment limited contamination by thermotolerant coliforms. This high hydrodynamic energy, primarily during the equinoctial spring tides, and the lack of urban planning, nevertheless generates other problems, such as coastal erosion. The following measures were recommended: (i) rationalize sewage disposal; (ii) removal of cesspits from the intertidal zone and dunes to avoid contact with groundwater and tides; (iii) implementation of a public sanitation system; (iv) continuous monitoring of water quality for the control of bathing areas, and (v) stricter urban planning and regulation to minimize pressures on coastal environments.

ADITIONAL INDEX WORDS: *Equatorial beach, coastal management, human impact on beaches.*

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2.2 Introduction

Coastal zones encompass complex natural environments that are vulnerable to the rapid urbanization and economic development that has taken place during the twentieth century (Cicin-Sain and Knecht, 1998; Irtem *et al*., 2005). These locations are prime areas for residential, commercial, industrial and harbor development (Carrero *et al*., 2009; Schlacher and Thompson, 2008). As a consequence, human activities have placed increasing pressure on coastal environments, including the (i) loss of habitats such as mangroves, reefs, dunes, and lagoons, (ii) increasing production of solid waste, (iii) decrease in water quality, and (iv) loss of infrastructure through erosion. The growing demand for services and infrastructure, and the increasing output of waste can not only affect the quality of beach water, but may even alter the natural features that attract beachgoers (Breton *et al*., 1996; Crawford, 2007; Pereira *et al*., 2007a; Mohanty *et al*., 2008; Ten Voorde, 2009). Beaches appear to be among the most vulnerable coastal environments, due primarily to their attractiveness as a site for leisure activities, and the development of related economic activities (Bauer and Sherman, 1999). The conservation and management of the coastal zone of the Amazon region – which includes the Brazilian states of Amapá, Maranhão, and Pará - demands special attention, given the richness of its natural resources and its unique configuration, immense tropical and mangrove forests, and the enormous output of freshwater and sediments from its river system (Meade *et al*., 1985; Geyer *et al*., 1996). Studies of the region's oceanographic processes are still rare, and effective management of the coastal zone is an enormous challenge for local governments (Szlafsztein and Sterr, 2007). In addition, the Pará State Coastal Management Program (GERCO-PA) has been relatively unsuccessful in comparison with similar programs in other Brazilian states.

The coastal zone of Pará can be divided into three geomorphologically-distinct sectors: (i) Atlantic coast; (ii) mainland estuary, and (iii) estuary islands. Due to its natural characteristics, the Atlantic coast is the most popular for recreational activities. In order to evaluate the effects of these activities in the context of the absence of adequate local planning for the regulation of land use and the control of water quality, the present study focused on the Atlantic coast beach of Atalaia, the most popular resort of this sector. This equatorial sandy beach receives relatively large numbers of beachgoers, especially during July which in the area is the touristic high season. The aim of the present study was to evaluate the impact of human activities on the characteristics of the beach in the context of its unique natural attributes, and to contribute to the development of guidelines for the implementation of effective coastal management programs.

2.3 Study Area

Atalaia beach (Figure 1) is located in the municipality of Salinópolis in northeastern Pará, 220 km from the state capital, Belém, and 13 km from the center of Salinópolis. Urban development is based on the tourism industry, which is essential to the local economy (Szlafsztein, 2005).

This 12 km-long dissipative beach is formed by elongated sandy ridges 200-400 m wide (low-high spring tide water levels) with a west-east orientation, surrounded by dunes, lagoons, and mangroves. Local tides are semidiurnal, with spring tide heights up to 5.5 m (DHN, 2010). Incident waves are normally from the northeast, with significant heights (H_s) between 0.4 and 1.3 m (CPTEC, 2010). The local climate is classified as Am' in the Köppen system, and has two distinct seasons, a wet season, normally between January and June and a dry season, from July to December (INMET, 2010).

In terms of land occupation, the beach has two distinct sectors: an east sector occupied mainly by simple wooden structures (bars, beach houses, and guest houses) on the dunes and intertidal zone, and a west sector dominated by private beach houses, mansions, and hotels, which extends much further inland.

2.4 Methods

Data were collected between November, 2008, and November, 2010. Four types of variables were analyzed: (i) physical variables (winds, precipitation, currents, waves, and tides), (ii) hydrological variables (water temperature, salinity, pH, turbidity, and concentrations of dissolved oxygen, nutrients, chlorophyll *a*, and thermotolerant coliforms), (iii) urban development, and (iv) spatial distribution of services and infrastructure.

Meteorological data (rainfall and wind) were obtained from the National Meteorological Institute between November, 2008 and October, 2009. Four campaigns of over 25 hours were conducted in November, 2008, March, 2009, June, 2009 and September, 2009. Hydrodynamic and hydrological data were obtained during spring tide periods. A mini-current meter, CTD (salinity and temperature), and wave and tide data loggers were bottom mounted at a depth of 1.7 m in the subtidal zone and programmed to collect mean data every 10 minutes.

For the measurement of hydrological data (pH, turbidity, dissolved oxygen and inorganics nutrients, chlorophyll *a* and thermotolerant coliforms), samples of subsurface water were obtained every 3 hours using Niskin oceanographic bottles. In the laboratory, the samples were analyzed according to the procedures of Strickland and Parsons (1968) for dissolved oxygen, Strickland and Parsons (1972) and Grasshoff *et al*. (1983) for dissolved nutrients. Chlorophyll *a* content and thermotolerant coliform abundance was determined by the methods of Parsons & Strickland (1963) and APHA (2005), respectively. Turbidity and pH were also measured in the laboratory. All the buildings on the waterfront were identified and georeferenced using a GPS in November, 2010.

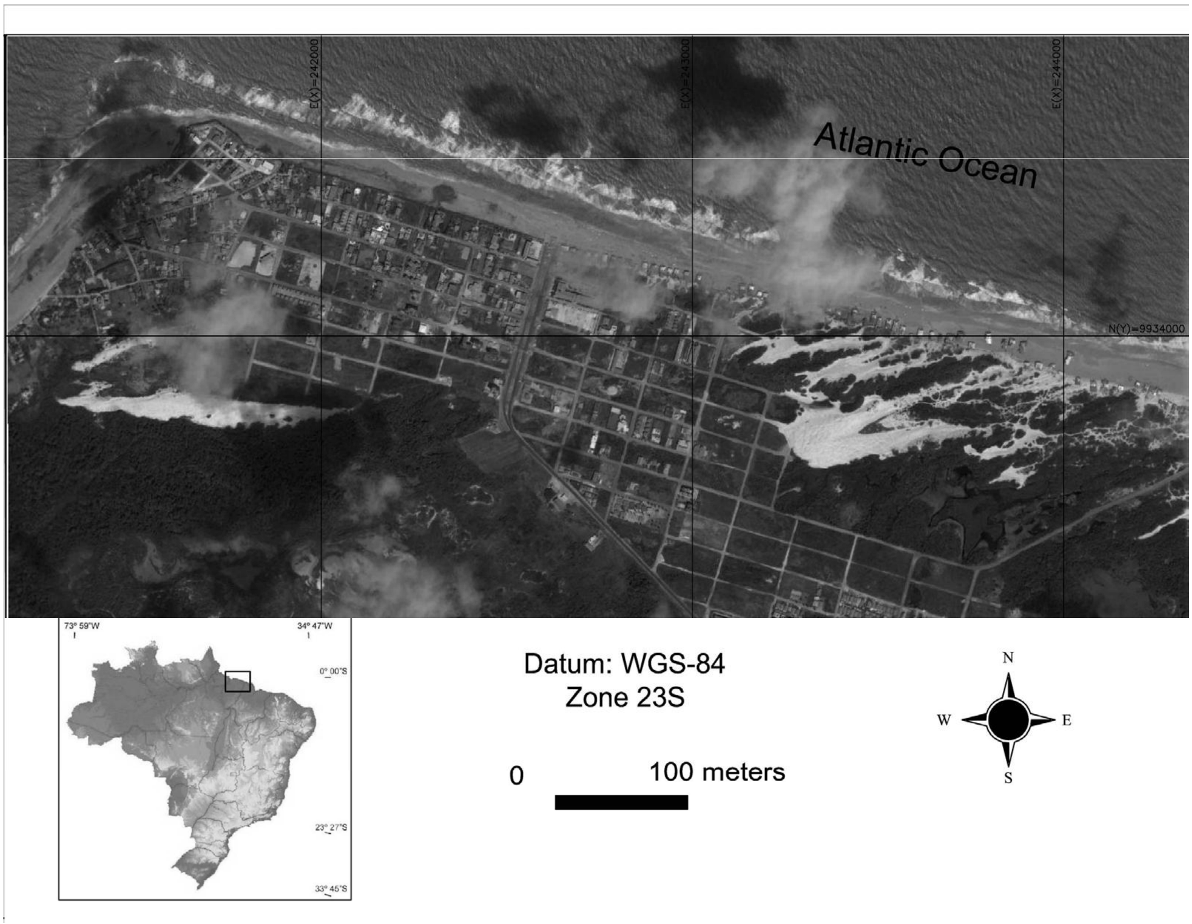

Figure 1. Location of the study area.

2.5 Results

2.5.1 Physical Variables

The highest monthly mean air temperatures (> 28°C) and wind speeds (> 3.5 m/s) and lowest precipitation levels (< 1 mm) were recorded during the dry season. Conversely, the highest monthly mean precipitation (> 300 mm) with the lowest temperatures (< 26.5°C) and wind speeds (< 2.3 m/s) were recorded during the wet season.

Local tides were semidiurnal and weakly asymmetric (flood tide up to 6:40 h in duration), with heights of up to 5.5 m during equinoctial spring tide events. Currents were mostly tidal with predominant northwest direction during the flood tide, and southeast direction during the ebb tide. Highest current speeds were recorded during the flood tide (maximal of 0.5 m/s in March and September), while maximal speeds of 0.4 m/s were registered during the ebb tide (March and June). Wave energy was modulated by the low tide due to wave attenuation on sand banks and during strong winds, H_s attained 1.5 m (November, 2008).

2.5.2 Water Quality

The lowest salinity (5.7), temperature (27.4°C), dissolved oxygen (5.92 mg/L) and pH (7.42) were all recorded in the wet season, as were the highest turbidity (up to 118 NTU) and the highest concentrations of dissolved nutrient (phosphate: 0.6 µmol/L; silicate: 329.7 µmol/L), and the lowest chlorophyll *a* (5.2 mg/m³) concentrations. Conversely, the highest salinity (up to 37.4), temperature (29°C), pH (up to 8.68), chlorophyll *a* (82 mg/m³) and the lowest dissolved nutrient concentrations (nitrite: 2.36 µmol/L , nitrate: 24.34 µmol/L) and turbidity (9.01 NTU) were recorded in the dry season. High concentrations of thermotolerant coliforms (> 1.100 MNP/100ml) were recorded only during equinoctial spring tide events (March and September), when the abnormally high tides reached the level of the cesspits located in the intertidal zone.

2.5.3 Urban Development

The east sector of the Atalaia waterfront is occupied mainly by simple wooden structures (guest houses, bars, and beach houses) built on the dunes or intertidal zone. This zone concentrates the highest number of beachgoers. In the west sector, the houses are built on a region strongly affected by erosive processes. This has led to the construction of sea walls and other protective structures (Figures 2A, B). In the east sector, by contrast, the wooden structures are transferred to new locations within the dunes whenever threatened by erosive processes.

Due to the lack of a public sanitation system or refuse collection, sewage and solid waste are deposited directly onto the beach. This study registered 50 cesspits and more than 15 sewage outlets along the beach (Figures 2C, D). Atalaia also lacks public water supply, and electricity supplies and street cleaning are intermittent. Vehicles are driven onto the beach and parked in the intertidal zone (Figures 2E-2G).

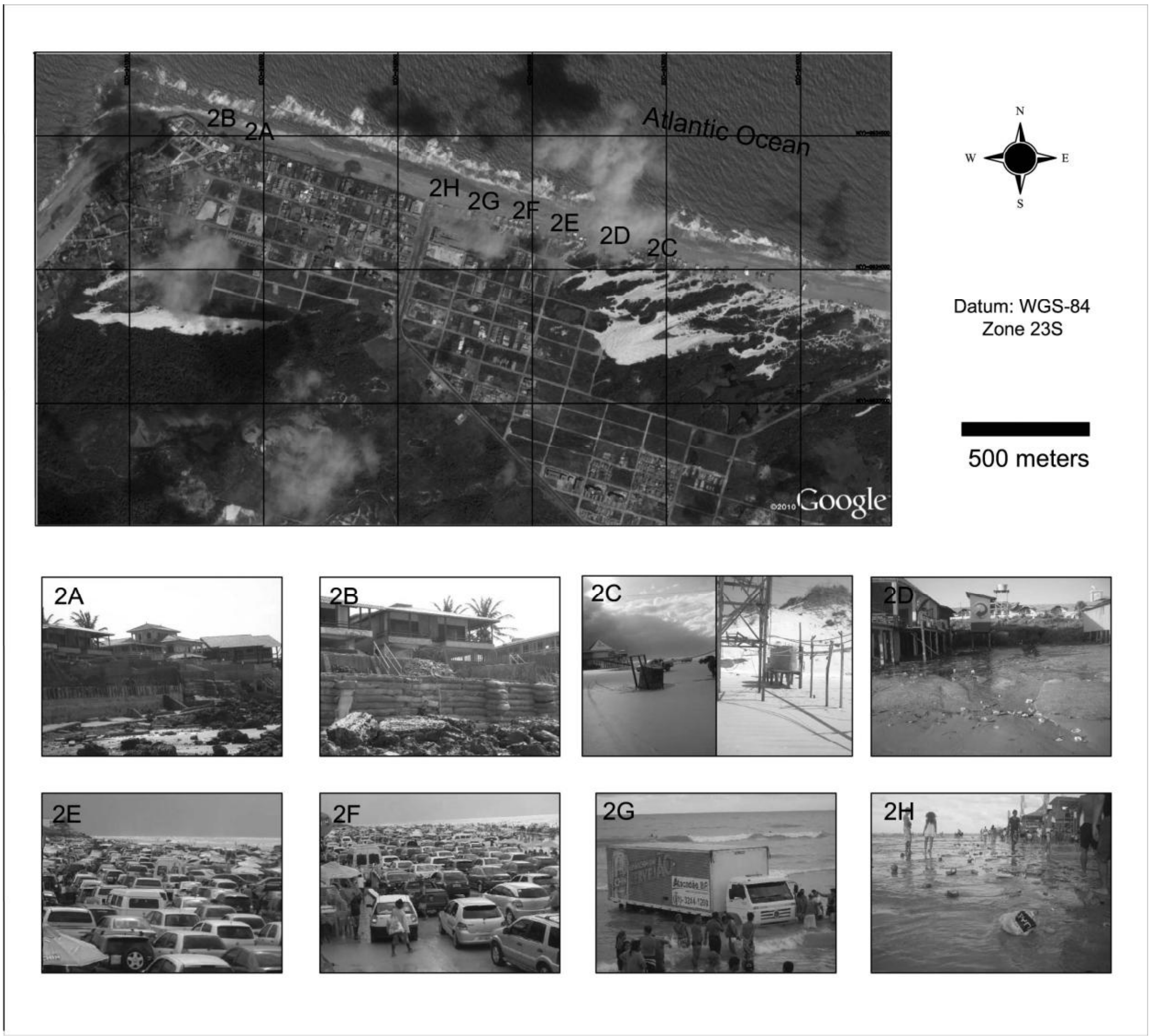

Figure 2. General conditions recorded in Atalaia beach.

The infrastructure of the waterfront includes 86 bars, 50 private houses, and five guest houses, 25 lamp posts, 7 garbage dumpsters, four public telephones, one car-park, a few shops, and one ATM. With the exception of the main access road, streets are no more than sandy tracks.

As Atalaia is considered to be the state's best beach, the east sector tends to get overcrowded during the peak vacation period (July), especially during weekends. The intense traffic in the intertidal zone during this period leads to crashes and other accidents (Figure 2G). There is also considerable increase in sewage discharge and the disposal of solid waste, including plastics, paper and metal, food leftovers, and human and animal excrement (Figures 2D, H).

2.6 Discussion

The high water turbidity, chlorophyll *a*, dissolved oxygen and nutrient concentrations registered throughout the year, as well as low salinity in the rainiest months are a consequence of the local natural conditions (for example, climate, hydrodynamical pattern and geomorphological features). A series of factors, including the macrotidal regime, strong tidal currents, northeasterly trade winds, high rainfall rates, substantial fluvial discharge, the irregular shape of the coastline (with countless estuaries and bays), and the presence of mangrove systems are the main responsible by control the hydrological variables in the studied area (Meade *et al*., 1985; Marengo, 1995; Kineke *et al*., 1996; Santos *et al*., 2008).

The unregulated occupation of the coastline and the lack of a public sanitation system appear to be the primary factors determining the bacteriological quality of the coastal waters. The high tides, mainly in March and September, reach the level of the cesspits located in the intertidal zone, contributing to the increasing of the bacteriological levels during the high tide period. However, the high hydrodynamic energy results in a rapid turnover and renovation of the water, which reduces contamination and the risks to public health. Similar results were obtained by Silva *et al*. (2009) at four urban beaches in São Luís (Maranhão state) where 101 outlets discharged sewage directly onto the beaches. Pereira *et al*. (2007a) have shown that, in more sheltered beaches, the water turnover is greatly reduced and bacteriological contaminations from sewage outlets may have considerable impacts on public health.

The lack of adequate traffic infrastructure is also a serious problem on many Amazonian beaches (Pereira *et al*., 2006; Silva *et al*., 2009), causing both intrinsic problems such as traffic jams and accidents, and environmental impacts. At Atalaia, the high concentration of vehicles also contributes to the overcrowding of the intertidal zone (Sousa *et al.*, in this issue).

Morphodynamic studies are urgent in this Amazon sector to know the local volumetric evolution. Studies made by Souza-Filho *et al.*, 2003; Alves and El-Robrini, 2006; Pereira *et al.*, 2007b; Monteiro *et al.*, 2009, Pereira *et al.*, 2009 and Szlafsztein and Sterr, 2007 - in other beaches located in northeastern Pará - showed that hydrodynamical, hydrographical and geomorphological characteristics associated to the unregulated construction of buildings in that coastal zone are the main factors responsible for the observed erosive processes.

The urban development of coastal areas creates problems throughout the World. Studies in Spain (Breton *et al.*, 1996), India (Mohanty *et al.*, 2008) and North Carolina (Crawford, 2007) have shown that the pattern of occupation of the coastal zone is determined primarily by local legislation. The occupation of dunes, cliffs, the intertidal zone or mangroves is prohibited by both Brazilian federal law number 7661 of May 16th, 1988, and by Pará state legislation (law number 5587/95). At Atalaia, illegal occupation of these areas, together with a lack of infrastructure and services, has negative implications for natural resources and consequently, for the local tourism industry, a situation repeated at a number of sites on the coast of Pará.

Coastal management in Brazil is regulated by federal law 7661, which instituted the National Coastal Management Plan (PNGC). In Pará, the state program (GERCO-PA) has had only limited success. Szlafsztein (2009) found a lack of interest on the part of public administrators or reduced priority for coastal environments, combined with a relative deficiency of financial resources and personnel, considering the size of the area. The results of the present study indicate a clear and urgent need for the implementation of a coastal management program within the Salinopólis area, which should involve local inhabitants, the scientific community, government agencies, and NGOs.

2.7 Final Considerations

The results of the study indicate that climatic and hydrological conditions were the main factors responsible for fluctuations in water turbidity, dissolved oxygen and nutrients, and chlorophyll *a* concentrations. The discharge of untreated domestic sewage was responsible for bacteriological contamination, although the rapid turnover of this high-energy hydrodynamic environment limits contamination by thermotolerant coliforms. This high hydrodynamic energy, primarily during the equinoctial spring tides, and the lack of urban planning generates additional problems, such as coastal erosion. The following measures are required to avoid further impacts on the local environment: (i) rationalize sewage disposal; (ii) removal of cesspits from the intertidal zone and dunes to avoid contact with groundwater and tides; (iii) urgent implantation of a public sanitation system; (iv) continuous monitoring of water quality and other variables (physical, ecological and social) of the coastal zone, in particular for the control of bathing areas, and (v) stricter urban planning and regulation to minimize pressures on coastal environments.

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CAPÍTULO III

3. OCEANOGRAPHIC CONDITIONS AND HUMAN FACTORS ON THE WATER QUALITY AT AN AMAZON MACROTIDAL BEACH*

3.1 Abstract

Atalaia beach is situated in the NE of the Brazilian state of Pará and is one of the most popular with tourists and local beachgoers. This paper describes the seasonal variation in the meteorologic and oceanographic characteristics of the study area, as well as the effects of the lack of a public sanitation system on the quality of the water used by beachgoers. Oceanographic campaigns were carried out between November 2008 and September 2009. The study area is characterized by high rainfall rates (> 1900 mm during the rainy season), NE winds with mean speeds of up to 4.36 m/s in the dry season and 3.06 m/s in rainy season, macrotidal conditions (tidal range > 4.0 m), moderate tidal current speeds (up to 0.5 m/s), and significant wave heights up to 1.5 m. Water temperature was relatively homogeneous (27.4ºC to 29.3ºC). Salinity varied from 5.7 (June) to 37.4 (November). The water was well oxygenated (up to 9.17 mg/L), turbid (up to 118 nephelometric turbidity units), alkaline (up to 8.68), and eutrophic (maximum of 2.36 µmol/L for nitrite, 24.34 µmol/L for nitrate, 0.6 µmol/L for phosphate, and 329.7 µmol/L for silicate), and it presented high concentrations of chlorophyll *a* (up to 82 mg/m^3). The natural conditions observed in the present study indicate the need for a review of the hydrologic criteria used for the evaluation of beaches by national and international agencies and their adaptation to the reality of the Amazon Coast. The lack of a public sanitation system has led to bacteriologic contamination and the loss of water quality.

ADDITIONAL INDEX WORDS: Natural conditions, anthropogenic activities, sewage, coastal zone, Amazon.

3.2 Introduction

Coastal zones encompass a variety of environments, many of which have been coming under growing pressure from ongoing urbanization and economic development. In recent years, the number and variety of human activities has been increasing progressively. In

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* Pereira, L.C.C.; Pinto, K.S.T.; Da Costa, K.G.; Vila-Concejo, A., And Da Costa, R.M., 0000. Oceanographic conditions and human factors on the water quality at an Amazon macrotidal beach. Journal of Coastal Research, 00(0), 000–000. West Palm Beach (Florida), ISSN 0749-0208.

addition to the exploitation of natural resources and recreational use, there is increasing pollution from industrial and residential development (Lau, 2005; Small and Nicholls, 2003; Steffy and Kilham, 2006).

The Amazon Coast encompasses the littoral zones of the Brazilian states of Amapá, Pará, and Maranhão, which together represent just over one-third of the country's 8.500 km coastline. This region includes one of the world's largest continuous tracts of mangrove forest (Lara, 2003) and is dominated by the discharge of numerous rivers, including the Amazon River, the world's largest by water volume.

Hydrodynamic patterns in this region are controlled by a series of factors, including the macrotidal regime, strong tidal currents, northeasterly trade winds, lack of Coriolis forces, high rainfall rates, and major fluvial discharge (Kineke et al., 1996; Marengo, 1995; Meade et al., 1985). Topographic features are also important: the continental shelf is both extensive and gently sloping, and the coastline is highly irregular, with innumerable bays, estuaries, and mangrove systems crisscrossed with tidal creeks (Nittrouer and DeMaster, 1986; Silva, Souza-Filho, and Rodrigues, 2009).

The coast of the northeastern portion of the state of Pará is typical of this scenario (Figure 1). The region is relatively densely populated, with 27% of the state's total population (IBGE, 2010), and local areas of the coastal zone have been impacted considerably by human activities over the past few decades (Gorayeb, Lombardo, and Pereira, 2009; Guimarães et al., 2009, Pereira et al., 2007, 2010; Souza-Filho, Martins, and Costa, 2006; Szlafsztein and Sterr, 2007).

Within this region, Atalaia has become one of the state's most popular beaches, which has resulted in increasingly intense development and occupation of the coastal zone in recent years, although this growth has not been accompanied by any adequate development of the public sanitation system, and sewage discharge onto the beach affects the quality of the water used for recreational activities (i.e., bathing, water sports). However, natural conditions, such as the region's massive fluvial discharge and high hydrodynamic energy, are responsible for the characteristics of its water, including high turbidity and pH and dissolved oxygen and nutrient concentrations, as well as its low salinity during rainy season. This suggests that the criteria of organizations such as the National Environment Council (CONAMA) and the Blue Flag Program need to be carefully reassessed and redefined for application to the evaluation of beaches on the Amazon Coast. In this context, the present paper aimed to evaluate the effects of seasonal fluctuations in meteorologic and hydrodynamic conditions on hydrologic and microbiological (thermotolerant coliform) variables. In addition, the implications of the lack of a public sanitation system for the quality of the water were analyzed.

3.3 Study Area

The study focused on the Praia de Atalaia, a beach on Atalaia Island in the municipality of Salinópolis, in the northeastern extreme of the Brazilian state of Pará (Figure 1). Salinópolis has a population of 39.180 and tourism is an important sector of the local economy (IBGE, 2010; PARATUR, 2010). Atalaia is very popular with local beachgoers and tourists, especially during the high season (July). However, the beach is a relatively long distance from the state capital and other major cities, and this, together with the prolonged and intense rainy season, has tended to limit development of the local tourist industry.

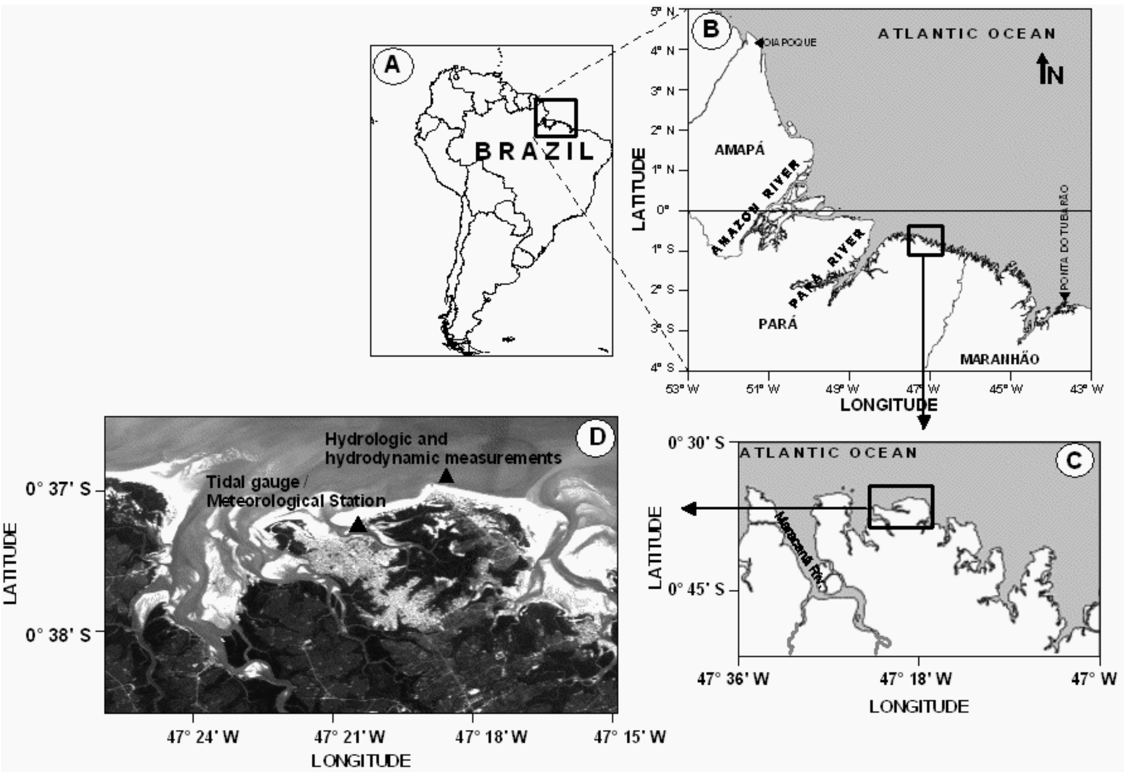

Figure 1. Study area: (A) South America, (B) Brazilian Amazon coastal zone, (C) part of the Pará state, and (D) Atalaia beach showing hydrodynamic and hydrologic station, and tidal gauge and meteorologic stations.

The beach is 12 km long and 200-400 m wide (low-high spring tide water levels). This macrotidal dissipative beach is bordered by the Atlantic Ocean to the north and east and by dune fields, mangroves, and buildings (bars, restaurants, houses, and hotels). There is no public sanitation system, and cesspits in the intertidal zone are a potential threat to the quality of the beach's water, especially in terms of bacterial contamination.

Tides are semidiurnal, with spring tide heights of up to 5.5 m (DHN, 2010). Data from the Weather Forecasting and Climatic Studies Center of the Brazilian Space Agency (CPTEC, 2010) show that prevailing offshore waves come from the NE, with significant wave heights (H_{os}), normally between 0.4 and 1.3 m. The local climate is classified as Am' in the Köppen system and is characterized by two distinct seasons (rainy and dry). Only 10-15 % of the annual precipitation falls during the dry season (normally from July to December), when mean temperatures are between 27ºC and 30ºC. The rainy season (January to June) is characterized by high precipitation rates (1500-2500 mm) low insolation and evaporation, and temperatures as low as 25ºC. The area is dominated by northeasterly trade winds (Geyer et al., 1996), and the highest average wind speeds are normally recorded during the dry season (INMET, 2010).

3.4 Methods

The present study was based on two complementary approaches. Hydrodynamic and hydrologic data were collected in four campaigns of 25 hours' duration between November 2008, and September 2009, distributed in such as way as to best sample seasonal differences, but during the tourist off season. The November 2008 sample represents the period of lowest fluvial discharge during the dry season, while that of March 2009 coincides with rising discharge during the rainy season, and June 2009 coincides with the period of highest fluvial discharge during the rainy season. Finally, September 2009, represents the dry season period of decreasing fluvial discharge.

The second approach involved the analysis of the meteorologic and hydrodynamic data collected daily by the respective Brazilian monitoring institutions during the same period.

Meteorologic data (wind speed, wind direction, and rainfall) were obtained from the Brazilian Institute of Meteorology's Salinópolis-A215 station (0º37'97.248" S, 47º21'93.96" W). Offshore wave data (H_{os} and direction) were obtained from the Weather Forecasting and

Climatic Studies Center of the Brazilian Space Agency (CPTEC-INPE) in order to contextualize the measurements obtained during the monthly campaigns.

The field campaigns were conducted at the spring tide during periods when few beachgoers were present. A mooring was mounted on the seafloor (1.7 m depth at low spring tide) at 00º37'11" S, 047º21'04" W (Figure 1), with a Sensordata SD 6000 minicurrent meter, a conductivity-temperature-depth recorder (CTD; XR-420, RBR), and a tide and wave recorder (TWR 2050) attached. Tidal currents were measured every 10 minutes, and their direction was recorded relative to the magnetic north. Waves were measured at a rate of 4 Hz (512 samples per 10 min). Tide data were acquired every 2 seconds, with mean values being obtained every 10 minutes.

Subsurface water samples were collected using a Niskin oceanographic bottle every 3 hours in the surf zone. In the laboratory, turbidity and pH were measured using a turbidity meter and pH meter, respectively. The procedure of Strickland and Parsons (1968) was used for the measurement of dissolved oxygen; the procedures of Strickland and Parsons (1972) and Grasshoff, Emrhardt, and Kremling (1983) were used for dissolved nutrients; and the procedure of Strickland and Parsons (1963) was used for chlorophyll *a*, while thermotolerant coliform levels were measured using the method of the American Public Health Association (APHA 2005).

For statistical analyses, the assumptions of normality and homogeneity of variance were investigated using the Lilliefors test (Conover, 1971) and Bartlett's Chi square (Sokal and Rohlf, 1969) run in the Statistica 6.0 package (StatSoft, 2001). When data were not normal, log (x + 1) transformations were conducted to provide near-normal distributions using version 6.1.6 of the Plymouth Routines Multivariate Ecological Research (PRIMER) statistical package (Clarke and Warwick, 1994). A one-way analysis of variance, followed by Fisher's least significant difference post hoc test were used to analyze monthly and seasonal fluctuations in physical, chemical, and microbiologic variables. However, when the variances were heterogeneous, the nonparametric Mann-WhitneyUtest or the Kruskal-Wallis test was used to investigate possible differences between months and seasons (Zar, 1999).

3.5 Results

3.5.1 Climate

A total of 1954 mm of precipitation was recorded in the study area during the rainy season, i.e., between January and June 2009 (Figure 2A). March was the rainiest month, with a total of 412.8 mm. By contrast, only 146.8 mm was recorded in the dry season months of November and December 2008, and July-September 2009. The overall mean air temperature was 27.2ºC, with monthly values varying from 25.95ºC in May to 28.90ºC in September (Figure 2A).

Wind speeds also varied seasonally (Figure 2B), with relatively strong winds (mean speed between 2.84 and 4.36 m/s, and maximum from 6.87 to 9.33 m/s) blowing from the NE during the dry season (Figure 2C). During the rainy season, winds were weaker, blowing from the NE, NW, SE, and SW (Figure 2C), with mean monthly speeds between 1.40 and 3.06 m/s and maximum speeds from 4.15 to 7.11 m/s (Figure 2B).

3.5.2 Hydrodynamic aspects

Tidal currents run predominantly SE-NW during the flood tide and NW-SE during the ebb tide (Figure 3). Highest current speeds were recorded in March and September, reaching a maximum of 0.5 m/s during the flood tide. In March and June (rainiest months), the ebb tide currents reached a maximal of 0.4 m/s.

The tidal cycle was weakly asymmetric (Figure 4), with the ebb tide lasting up to 6 hours 40 minutes. High tides reached between 3.9 and 5.3 m, with the highest tides recorded during the equinoctial spring tides of March and September.

Wave energy was modulated by the low tide due to wave attenuation on sand banks (Figure 4). Maximum wave height-H_s values (0.8-1.5 m) were recorded in November, and the lowest were recorded in June (generally lower than 1.2 m). Offshore wave data from CPTEC-INPE (Figure 5) indicated a predominance of waves from the NE during the study period. November, March, and September had higher-energy offshore wave conditions, with H_{os} values generally above 1 m. June was characterized by much lower-energy wave conditions ($H_{os} < 1$m).

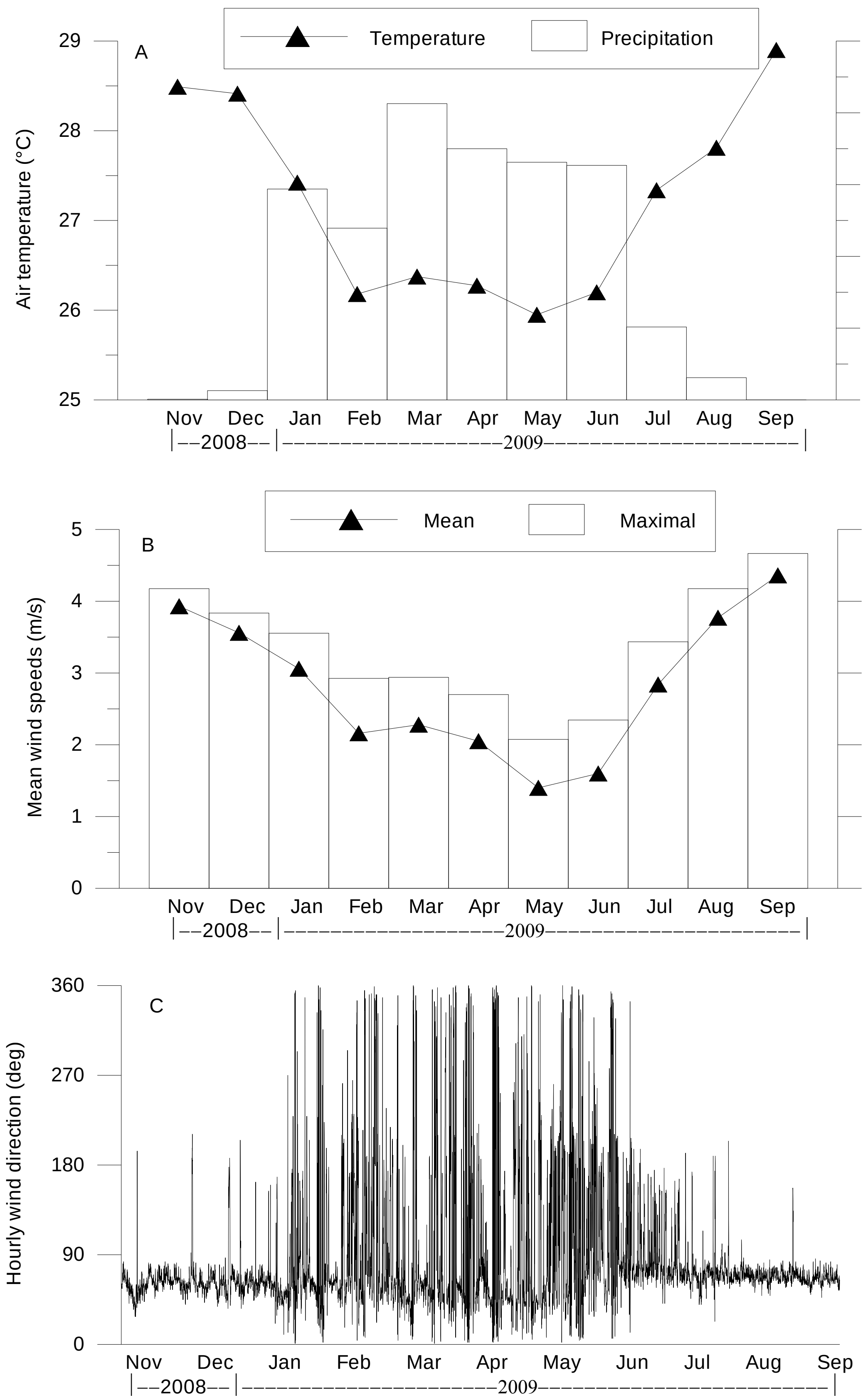

Figure 2. Climate data for the study area, obtained from Instituto Nacional de Meteorologia's Salinópolis-A215 station.

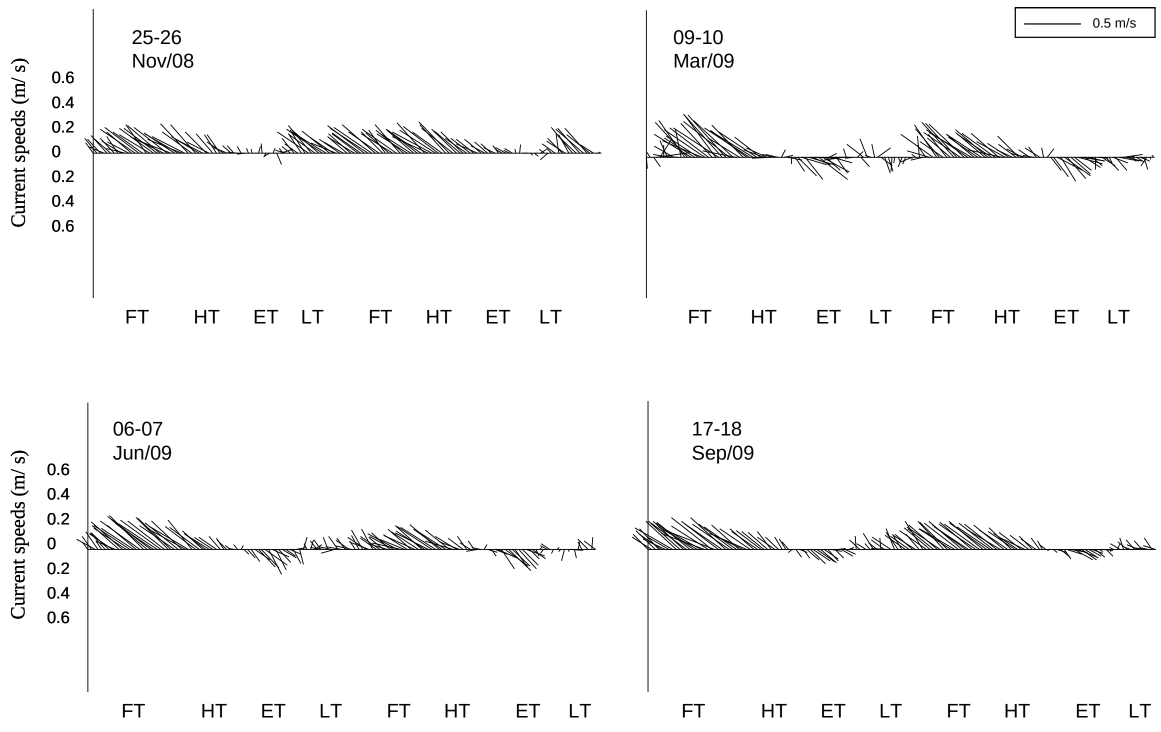

Figure 3. Coastal current speed (m/s) and direction at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

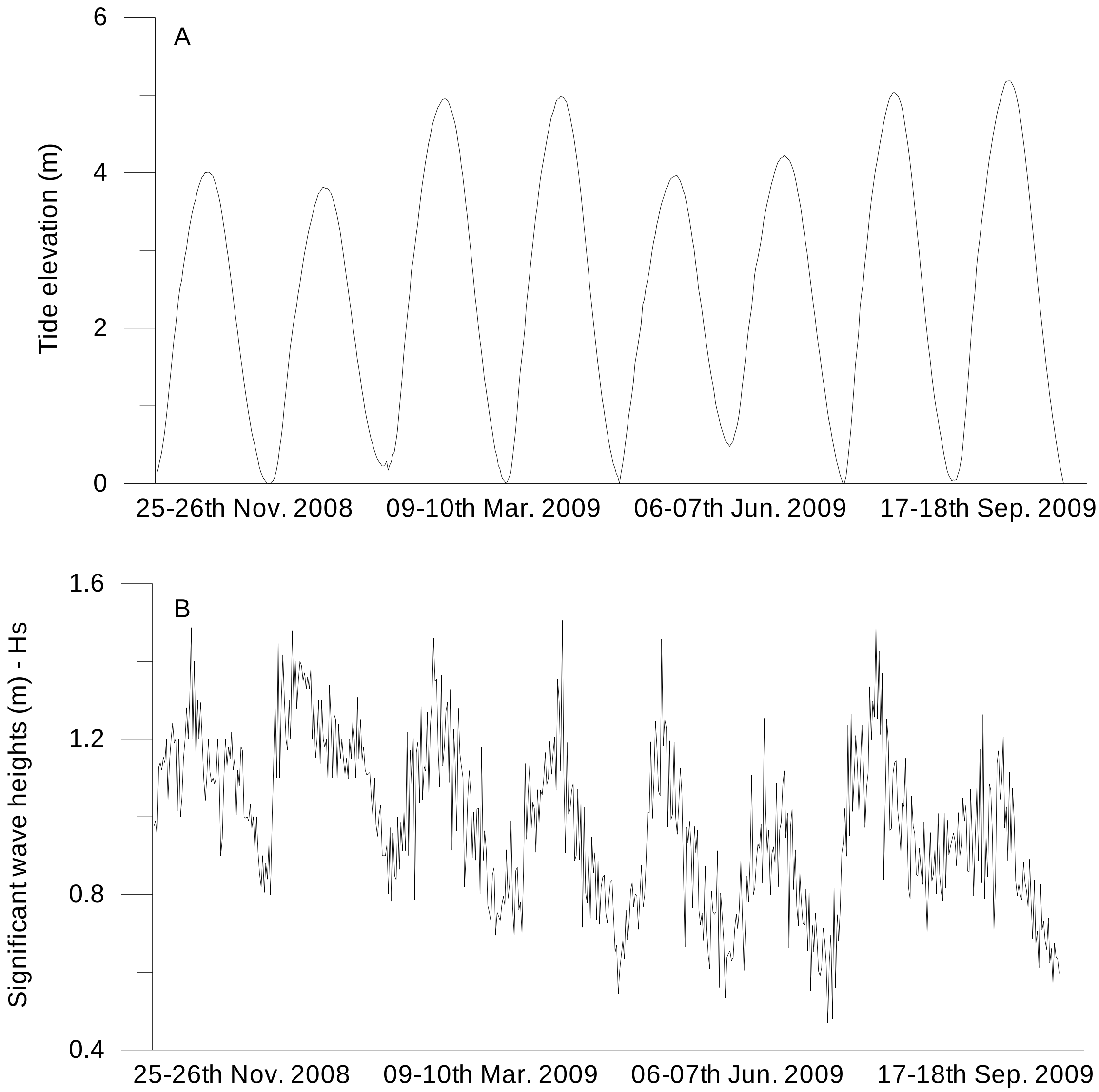

Figure 4. Tide ranges (m) and significant wave heights (m) recorded at Atalaia beach during the studied period.

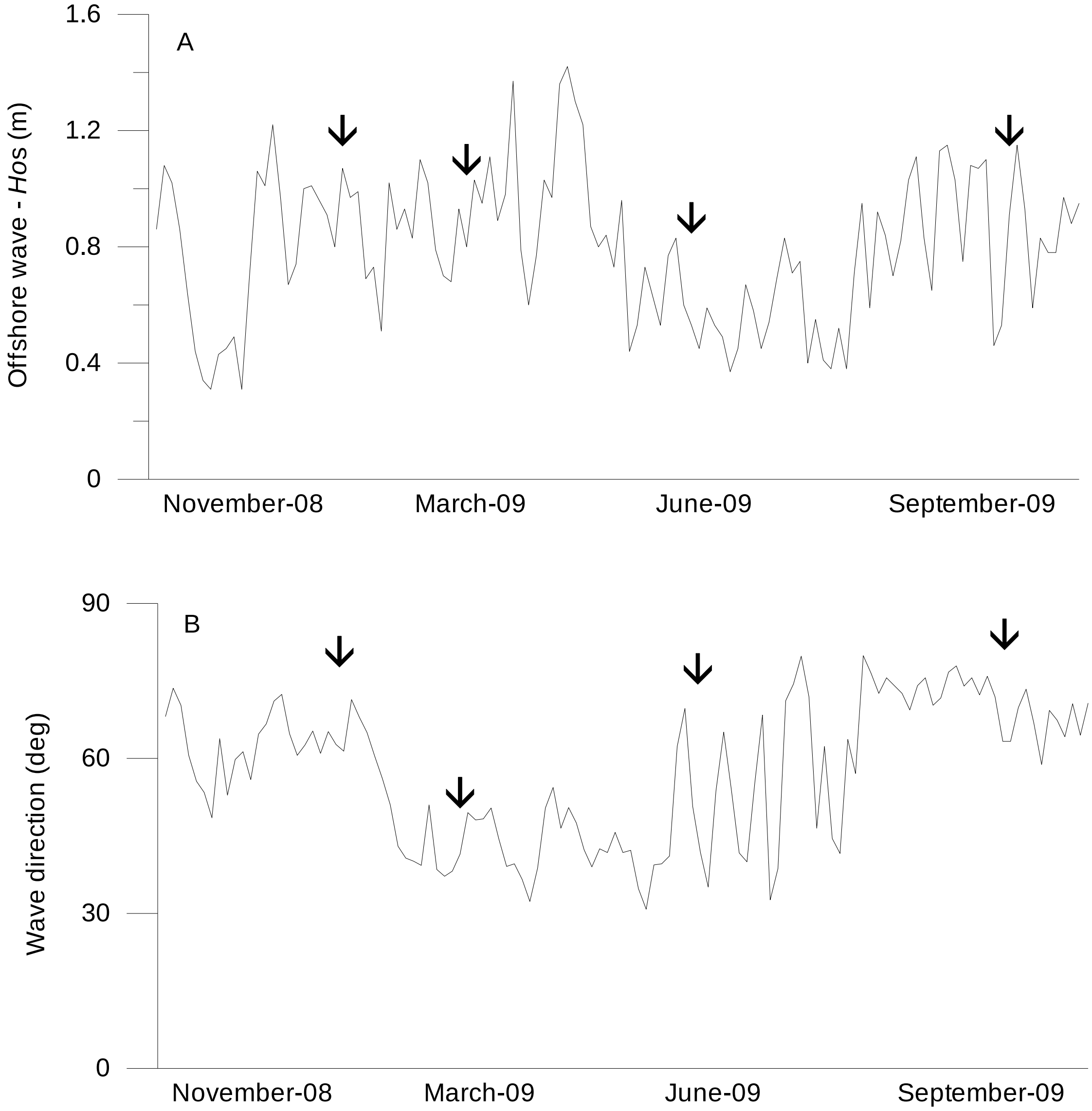

Figure 5. Offshore wave data. The arrows (↑) indicate the days on which data were collected in the present study.

3.5.3 Hydrology aspects

Average water temperature ranged from 27.6ºC to 29.3ºC during the study period, with the highest values being recorded during the dry season, when insolation was at its highest. There was substantial diurnal variation, with the highest temperatures occurring between 12:00 and 18:00 hours, and the lowest from 00:00 to 06:00 hours (Figure 6). Salinity was highest in November, when rainfall and fluvial discharge were lowest, with values between 34.6 and 37.4. Salinity was lowest in June (5.7-8.8), the rainy season month characterized by the highest fluvial discharge (Figure 6).

Dissolved oxygen concentrations (Figure 7A) were highest in September (7.6-9.17 mg/L), presumably reflecting the relatively strong tidal currents and winds of this period, while these were lowest in March (5.92-7.31 mg/L). Monthly (F = 25.874; p = 0.000) and seasonal (F = 10.661; p = 0.002) values were significantly higher during the dry season.

A similar, but inverse pattern was recorded for turbidity, which was highest in the rainy season (U = 90.00; p = 0.022) and in particular during June (H = 26.27; p =.000). Turbidity was lowest during November (period of least rainfall and lowest fluvial discharge) ranging between 9.01 and 14.83 nephelometric turbidity units (NTU). As mentioned above, the highest values were recorded in June (flood tide, 25.56 NTU; ebb tide, 118 NTU), coinciding with the period of greatest fluvial discharge, with the highest values recorded during the ebb tides (influence of the fluvial discharges) (Figure 7B).

Significant monthly (F = 16.405; p = 0.000) and seasonal (F = 44.387; p = 0.000) variation was also observed in pH, with the higher values (8.12-8.68) being recorded in November, a period of low rainfall and high salinity. The lowest pH values (7.42-8.00) were recorded in the rainy season months of March and June (high rainfall and low salinity) (Figure 7C). Chlorophyll *a* concentrations (Figure 7D) varied significantly among months (H = 32.84; p = 0.000) but not between seasons. While the highest values were recorded in November (42.4-82.0 mg/m^3), the lowest were observed in June and September (5.2-16.7 mg/m^3), coinciding with the lowest and highest turbidity values, respectively.

As for chlorophyll-*a*, dissolved nutrient concentrations varied significantly among months (nitrite, H = 32.89; p = 0.000; nitrate, H = 32.84; p = 0.000; phosphate, H = 32.85; p = 0.000; silicate, H = 20.64; p = 0.000) but not between seasons. The highest nitrite concentrations (1.49-2.36 µmol/L) were recorded in September (equinoctial spring tide), whereas the lowest values (0.16-0.17 µmol/L) were obtained in November (Figure 7E), coinciding with the highest concentrations of chlorophyll *a*. Nitrate concentrations were also relatively high in September (2.50-24.34 µmol/L), while the lowest values were observed in November and March (Figure 7F), once again coinciding with increased chlorophyll *a*. By contrast, the lowest phosphate (0.15-0.36 µmol/L) and silicate (11.5-45.0 µmol/L) concentrations were recorded in March, while they were highest in June (phosphate, 0.35-0.60 µmol/L; silicate, 186.0-329.7 µmol/L), presumably reflecting the high fluvial discharge during this period (Figures 7G/H).

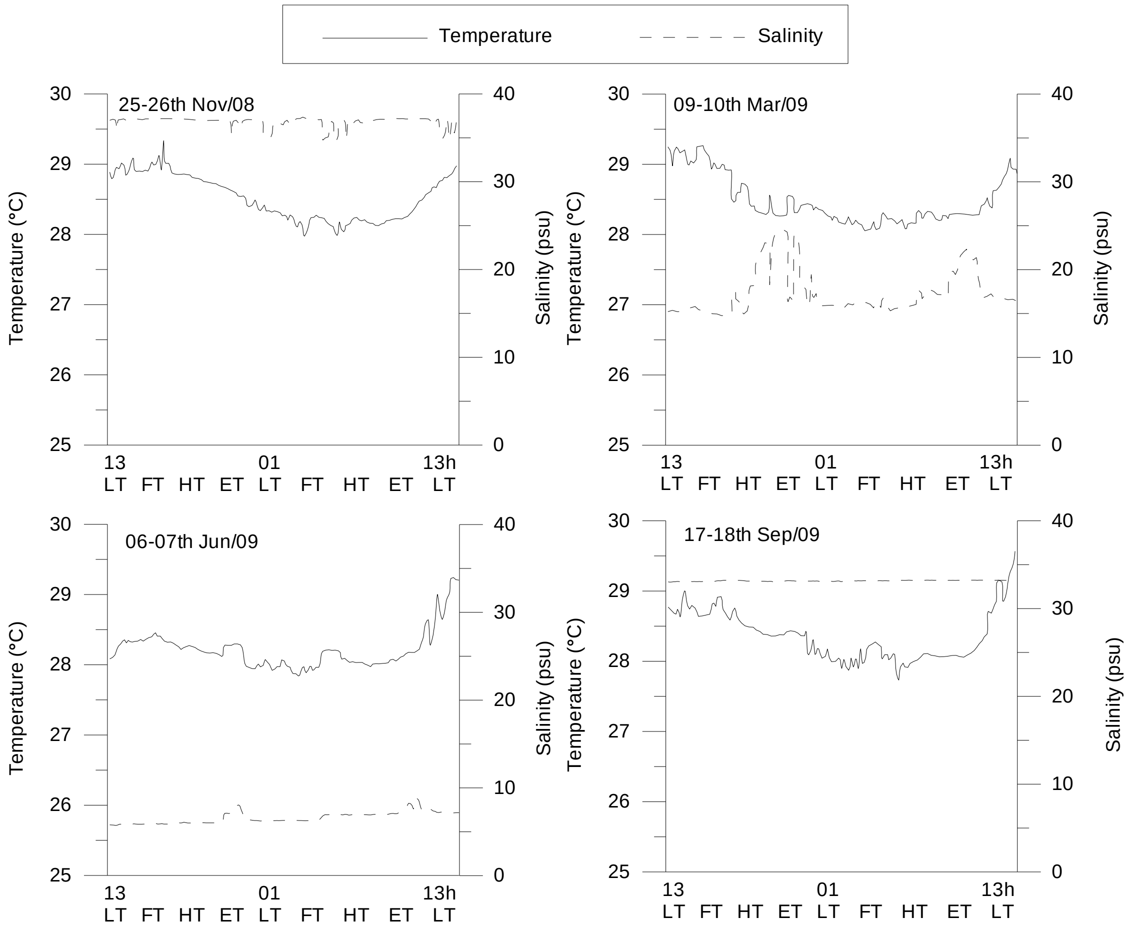

Figure 6. Water temperature (°C) and salinity at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

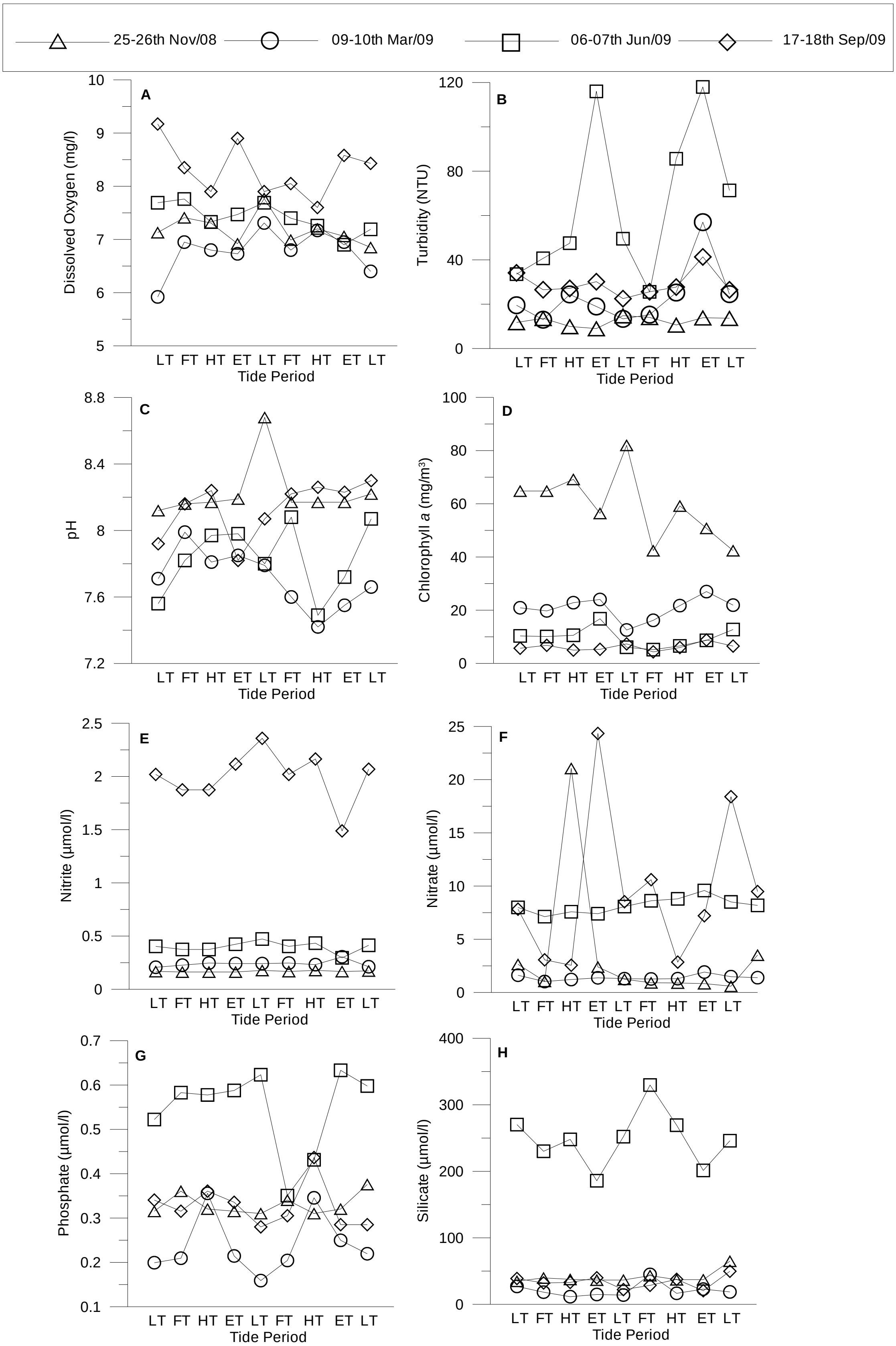

Figure 7. Hydrologic measurements taken at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

Around a third of samples analyzed presented concentrations of thermotolerant coliforms above 1100 most probable number (MPN)/100 ml. Concentrations were highest in March and September (Figure 8), when the equinoctial spring tides reached the level of the cesspits constructed in the intertidal zone. A recent observation recorded 50 cesspits and at least 15 sewage outflows within the study area (Figure 9). Thermotolerant coliform concentrations varied significantly among months (F = 3.9095; p = 0.01739), but not between seasons.

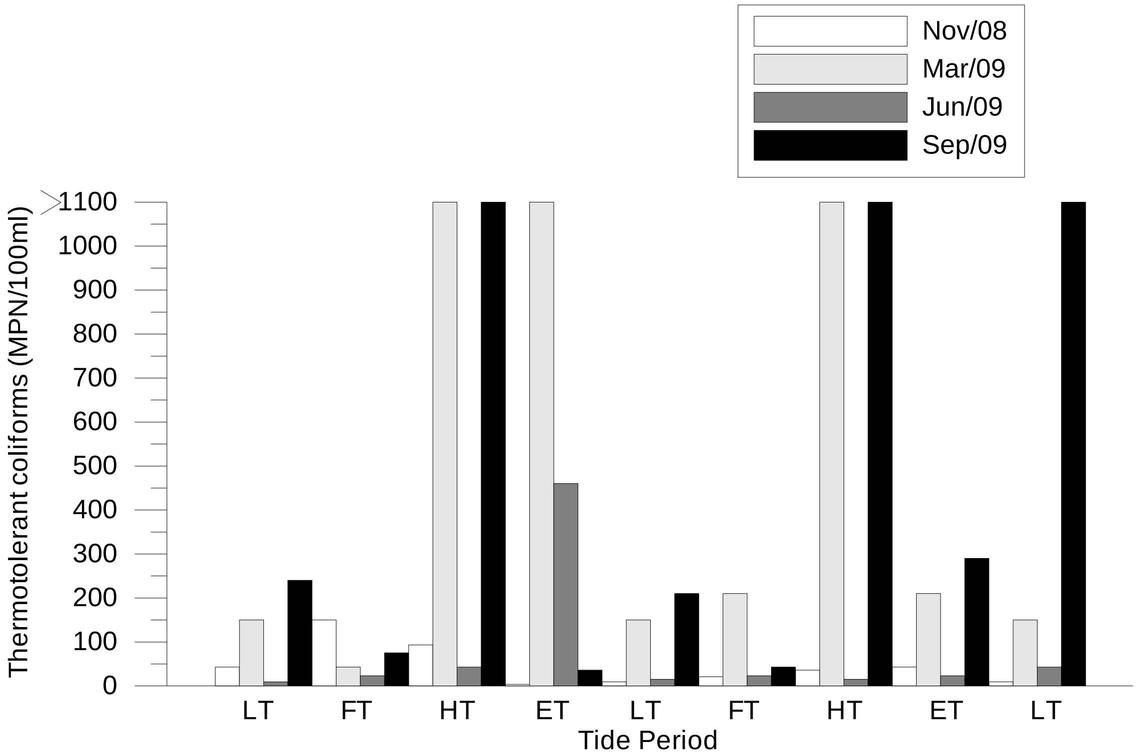

Figure 8. Thermotolerant coliform data (MPN/100 ml) at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

Figure 9. Study area during low tourist season ([A] restaurant buildings and [B] restaurants' facilities on the beach), the presence of cesspits and sewage (C-D) and high tourist season (E-F).

3.6 Discussion

Physical processes and water quality in Atalaia beach presents two distinct seasons, with high precipitation rates in the first half of the year and a marked dry period in the second half. Similar seasonal patterns have been recorded over the long term (23-y data series) for Pará as a whole (Moraes et al., 2005). The Intertropical Convergence Zone (ITCZ) is one of the main determinants of climatic patterns in this equatorial region. In the first semester, it moves to the Southern Hemisphere, resulting in an increase in precipitation and a reduction in temperature. During the second semester, the ITCZ moves northward, provoking a reduction in precipitation rates and an increase in air temperatures (Figueroa and Nobre, 1990; Marengo, 1995). Wind speeds also increase during this period, while more moderate speeds are typical of the rainy season, except for occasional strong gusts (Martorano et al., 1993; SEPOF, 2008).

The study area is dominated by macrotidal conditions with strong tidal currents and low to moderate significant wave heights (H_s). Nearshore and offshore wave conditions showed similar patterns. The highest hydrodynamic energy conditions were recorded in November, and during the equinoctial months of March and September, when both tides and waves attained their greatest heights, and coastal currents were strongest. By contrast, the lowest-energy hydrodynamic conditions were recorded in June, when the lowest wind speeds, wave heights, tidal range, and current speeds were recorded. Within the study area, the orientation of the coast associated with the typical northeasterly winds enhanced the propagation of waves, although tidal asymmetry is less pronounced than that at other sites on the Amazon Coast. This may be related to the fact that Atalaia is located within an area of lower fluvial sediment input, which reduces the potential for the formation of sandbanks or long-shore bars, allowing the flood tide to reach the beach quickly, rather than being trapped in these features, as observed at the nearby Ajuruteua beach (Monteiro, Pereira, and Oliveira, 2009), where the extensive sandbars formed by the Caeté River contribute to a much stronger asymmetry, with an ebb tide of around 7 hours 30 minutes during the spring tides.

The highly seasonal climate and associated variation in hydrodynamic conditions combined to determine the observed seasonal fluctuations in hydrologic variables. Salinity and pH were significantly lower in the rainy season, as a result of both high precipitation rates-especially in March-and increased fluvial discharge, culminating in June. Fluvial discharge data are not available for the smaller rivers in the Amazon region, but studies undertaken by Curtin and Legeckis (1986) showed that the peak discharge of the Amazon River occurs in May-June (2.3 x 10^5 m³/s), and the minimum discharge between October and December (0.9 x 10^5 m³/s).

River discharge in the region is therefore three times larger in May-June than in October-December, which is coincident with the lowest and highest water salinity and pH in the study area. Similar patterns have been recorded at other sites along the Amazon Coast, with salinity varying from ,10 in May and June to 35 in October-December, and pH varying from slightly acid to alkaline between the same periods (Costa, Leite, and Pereira, 2009; Guimarães et al., 2009; Leite, Pereira, and Costa, 2009; Pereira et al., 2009; Silva et al., 2009).

High oxygen concentrations (>5 mg/L) appear to be typical of the waters of the Amazon coastal zone (Costa, Leite, and Pereira, 2009; Pereira et al., 2010; Silva et al., 2009), but while some studies (Guimarães et al., 2009; Santos et al., 2008) have related an increase in dissolved oxygen to phytoplankton growth, the main determinant in the present study appeared to be the intensity of the water-atmosphere interaction. In September, when the highest oxygen concentrations were recorded, the hydrodynamic regime was characterized by strong winds and high (equinoctial) tides. An additional factor may have been the fact that the samples were collected in a zone of high turbulence, i.e., the surf zone (Silva et al., 2009; Sousa et al., 2009).

The highest turbidity was also recorded in the rainy season month of June, when fluvial discharge was at its greatest, but it was also relatively high in the equinoctial months of March and September, when the high tides generated strong hydrodynamic conditions. In terms of suspended sediment, the waters flowing onto the Amazon continental shelf are highly turbid due to the high sediment load of the Amazon River (which has one of the highest discharge rates in the world). In addition, the Amazon macrotidal mangrove coast is traversed by 23 estuaries, which provide a plentiful supply of fluvial sediments (Silva, Souza-Filho, and Rodrigues, 2009). However, Atalaia is situated east of the Amazon River and adjacent to estuaries of relatively modest size, with reduced water discharge and turbidity in comparison with other beaches in the region (Monteiro, Pereira, and Oliveira, 2009; Silva et al., 2009).

On the Amazon Coast, chlorophyll *a* concentrations are generally considered to be an index of the density of microalgae. In the present study, the highest concentrations were recorded in November (second highest was in March), when the water was less turbid, and sunlight penetration was at its maximum. An additional factor may have been the great wave heights (H_s) and relatively strong tidal currents recorded during those periods, which may have contributed to the increase in chlorophyll *a* due to the resuspension of phytobenthic species into the pelagic environment (Pereira et al., 2010; Sousa et al., 2008, 2009).

The vast and complex estuary system found on the Amazon Coast is an important source of nutrients for the continental shelf (Edmond et al., 1981). DeMaster and Pope (1996) recorded high concentrations of dissolved nutrients on the Amazon continental shelf resulting from both the input from the mangrove system and the resuspension of fine-grained and organic sediments by the strong tidal currents. In the present study, highest dissolved inorganic nutrient concentrations were recorded in September (nitrite and nitrate) and June (phosphate and silicate). In September, this pattern was likely due to the high equinoctial tides reaching the most elevated parts of the mangrove (mangrove supply), and the high hydrodynamic energy (strong currents and waves), which favored the resuspension of nutrients from the bottom. In addition, we also observed an increase of sewage discharge onto the beach in September (equinoctial spring tide-dry season) in comparison with March (equinoctial spring tide-rainy season) as a result of a slight increase of beachgoers during the dry season. In June, the primary factor was the high fluvial discharge. Whereas Edmond et al. (1981) and DeMaster, Kuehl, and Nittrouer (1986) recorded algal blooms on the Amazon shelf during periods of high nutrient concentrations, in the present study, the highest chlorophyll *a* concentrations were recorded in the months with the lowest nutrient concentrations (November and March), but in substantial amount. It seems possible in those months, at least, the algal bloom were related to low turbidity. Overall, the results of this study indicate that physical processes are the main factors responsible for the high considered inappropriate for recreational use, based on the turbidity, high chlorophyll *a*, high dissolved oxygen and nutrient concentrations, and low salinity (rainiest months) of the water in the study area. While the high turbidity and algal blooms appear to be a natural phenomenon, the beach would be criteria of CONAMA (2005) and the Blue Flag Program (2007). These water criteria demand, for example, virtually no turbidity or abnormal changes in the water color. The turbidity in the study area-and other beaches of the region-is a result of high fluvial discharge and hydrodynamic energy, whereas the phytoplankton blooms in the study area were a combination of the dissolved nutrients supply and a period of higher light penetration. Thus, it seems clear that the values used by these authorities are inappropriate for the unique natural conditions prevailing on the Amazon Coast and that the criteria should be carefully reassessed and redefined for application in this region, which presents estuarine characteristics during the rainy season and marine characteristic during the dry season.

3.6.1 Human Influence

Bacteriologic contamination indicates the effects of anthropogenic pressures on Atalaia beach. The results of this study have shown that the beach’s water, which is used intensively for recreational purposes (bathing, water sports), has been affected by bacterial contamination (thermotolerant coliforms) during low peak season (Figures 9A-B), as a result of unregulated occupation of the coastline and the lack of a public sanitation system. The presence of cesspits in the intertidal zone and the discharge of domestic sewage directly onto the beach (Figures 9C-D) are the primary factors determining the bacteriologic quality of the water. The high thermotolerant coliform concentrations (> 1100 MPN/100 ml) observed during the equinoctial spring tide events (March and September) indicate that the exceptionally high tides typical of this period reached the level of the cesspits in the intertidal zone. This is also the time of year when local residents empty their cesspits, which further contributes to the contamination of the beach's water, which has become inappropriate for recreational use, according to CONAMA and Blue Flag criteria. Contamination levels may have been underestimated here, given that the peak vacation period (July) was not sampled (Figures 9E-F), and the area's high hydrodynamic energy implies a rapid turnover and renovation of the water. The high dissolved nutrient concentrations recorded in September may also have been related to the lack of a public sanitation and drainage system associated with a slight increase of beachgoers. Previous studies have shown that the discharge of sewage in urban areas of the Amazon Coast has been contributing to increasing contamination of both estuarine and coastal marine waters (Guimarães et al., 2009, Silva et al., 2009).

3.7 Final Considerations

The characteristics of the water used for recreation in the study area were influenced by seasonal climatic patterns, hydrodynamic conditions, and human activities. Fluvial discharge and equinoctial spring tides were the main factors controlling the seasonal oscillations of hydrologic variables. Bacteriologic contamination resulting from the sewage discharged directly onto the beach proved to be the main factor affecting local water quality. This work showed that environmental characteristics of the Amazon beaches are completely different from other Brazilian beaches. So, specific evaluation criteria on environmental aspects must be elaborated for this region. Further studies in other Amazon beaches are also necessary to determine appropriate index values of hydrologic variables regarding the choice of proper standards of water quality. A number of measures would help to improve the quality of the water at Atalaia beach, including: (i) regulation of sewage disposal by both commercial and residential premises; (ii) removal of cesspits from the intertidal zone and dune system in order to eliminate contact with groundwater and adjacent marine coastal waters; (iii) immediate implementation of a public sanitation system or at least a regular cesspit drainage protocol; (iv) continuous monitoring of the physical, ecologic, and social elements of the coastal zone in order to guarantee adequate delimitation of proper and improper bathing areas, mainly during the peak tourism season; and (v) regulation of land use to reduce pressures on the coastal environment. These measures should improve prospects for the development of the local tourism industry and thus contribute to the expansion of the local economy without affecting the environment adversely. Coastal management guidelines, which could include specific legislation, policies, and supporting infrastructure for sustainable development, appear to be vital to the future of this sector of the Amazon Coast.

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3.10 Resumo

A praia de Atalaia está situada no nordeste do estado do Pará (Brasil), e é uma das mais turísticas e populares praias do litoral amazônico. O objetivo deste trabalho foi descrever as variações sazonais das condições meteorológicas e oceanográficas da área estudada, bem como conhecer os efeitos da falta de um sistema público de saneamento básico sobre a qualidade da água utilizada para banho pelos usuários desta praia. Campanhas oceanográficas foram realizadas entre novembro de 2008 e setembro de 2009 e dados meteorológicos foram fornecidos pelo Instituto Nacional de Meteorologia. Os resultados mostraram que a área de estudo é caracterizada por possuir altas precipitações (> 1900 mm durante o período chuvoso), ventos de nordeste com velocidades médias de até 4,36 m/s no período seco e 3,06 m/s no período chuvoso, macromarés com alturas acima de 4,0 m, correntes de marés com velocidades médias de até 5 m/s, e altura de ondas significantes de até 1,5 m. A temperatura da água foi relativamente homogênea (27,6 a 29,3ºC). A salinidade variou de 5,7 (junho) a 37,4 (novembro). A água foi bem oxigenada (até 9,17 mg/L), turva (até 118 NTU), alcalina (até 8.68), eutrófica (máximo de 2,36 µmol/L para nitrito, 24,34 µmol/L para nitrato, 0,6 µmol/L para fosfato e 329,7 µmol/L para silicato), e apresentou altas concentrações de clorofila *a* (até 82 mg/m³). As condições naturais observadas no presente estudo indicam a necessidade da revisão dos critérios de qualidade da água das praias amazônicas, estabelecidos por agencias nacionais e internacionais. Por outro lado, a falta de um sistema público de saneamento tem causado contaminação bacteriológica e comprometido a qualidade da água da praia de Atalaia.

CAPÍTULO IV

4. MORPHODYNAMICS CHARACTERIZATION IN A COAST DOMINATED BY TIDAL PROCESSES (ATALAIA BEACH, AMAZON LITTORAL)

4.1 Abstract

Beach morphology, waves, tides and current measurements were conduced on a moderate-energy macrotidal coastline of the Amazon coast (Atalaia, Brazil). The conceptual model proposed by Masselink & Short (1993) was used to determine the morphodynamic state. The present study was based on two complementary approaches: (i) hydrodynamic and topographic data collected in four campaigns of 25 hours duration during equinoctial and non-equinoctial periods, and (ii) climatological data (wind speed, wind direction, and rainfall) obtained from the Brazilian Institute of Meteorology. Field campaigns were conducted during spring tides and a mooring was mounted on the seafloor at a depth of 3.8 m below MLW, with a Sensordata SD 6000 minicurrent meter, and a tide and wave recorder (TWR 2050) attached. Topographic surveys were performed using a topographic level. Surface sediment samples were collected along the beach profile. Sediment samples were later separated in laboratory using a sieve shaker (rotap) with sieve nest ranging from -1.0 to 4.0 ϕ. Results showed that tidal currents run predominantly to the northwest during flood tides and southeast during the ebb tides. The highest current speeds were recorded during equinoctial period, reaching a maximum of 0.5 m/s in the flood tide. In March and June (rainiest months), ebb tide currents reached a maximal of 0.4 m/s. Tidal cycle was weakly asymmetric with the ebb tide lasting up to 6 hours 40 minutes. High tides ranged between 4 m (November) and 5.7 m (September), with the highest tides during the equinoctial spring tides. Wave energy was slightly modulated by the low tide due to wave attenuation on sand banks, but it was not observed substantial changes during ebb and flood tides. Modal wave height (H_b) varied from 1.1 to 1.43 m, associate to wave periods of 5.7-7.5 s, with maximal values were recorded in November (strong wind intensities). Dissipative conditions were found during high and moderate hydrodynamic energy (equinoctial and non-equinoctial condition), but in November the highest wave heights generated barred dissipative characteristic, whereas during the other months non-barred characteristics dominated.

Key-word: *modal wave, macrotidal beach, Amazon littoral.*

4.2 Introdução

Em praias naturais, os processos morfológicos são predominantemente influenciados pela interação de ondas e marés (Davis & Hayes, 1984; Masselink & Short, 1993). Assim, variações no comportamento morfodinâmico praial estão condicionadas basicamente às oscilações das condições hidrodinâmicas (Carter & Woodroffe, 1995; Weschenfelder & Ayup Zouain, 2002; Calliari *et al.*, 2003), bem como à configuração morfológica da região costeira e plataforma continental adjacente, além do estoque sedimentar disponível (Wright *et al.*, 1985; Weschenfelder & Ayup Zouain, 2002; Scott *et al.*, 2007; Camacho-Valdéz *et al.*, 2008).

Por algumas décadas, os estados morfodinâmicos de uma praia foram avaliados em função das características das ondas e sedimentos em ambientes de micromarés (Wright & Short, 1984). Entretanto, Masselink & Short (1993) tendo como base trabalhos anteriores (Short, 1984; Short, 1991) examinaram, em praias de macromarés, o efeito das ondas e marés na morfologia praial com o auxílio de um novo parâmetro, o alcance relativo da maré. A partir de então, os parâmetros da velocidade de queda adimensional (Short, 1987) e de alcance relativo da maré (Masselink & Short, 1993) estão sendo considerados nos estudos de morfodinâmica de praias de macromarés ao longo do mundo (Masselink & Hegge, 1995; Jackson *et al*., 2005; Scott *et al*., 2007).

Em regiões equatoriais sujeitas à elevada descarga fluvial e sedimentar, como a costa Amazônica, existem poucos estudos retratando as variações sazonais do estado mofodinâmico (Alves & El-Robrini, 2006; Pereira *et al*., 2009; Monteiro *et al*., 2009; Silva *et al*., 2009). Nestas localidades, as variações morfodinâmicas são constantemente alteradas por fatores de origem naturais e antrópicas (Krause, 2002; Souza-Filho *et al*., 2003; Pereira *et al*., 2006; Pereira *et al*., 2007).

Atalaia está localizada no nordeste do estado do Pará, e é uma das mais frequentadas durante o período de veraneio (Sousa *et al*., 2011; Pinto *et al*., 2011). Esta praia é relativamente mais exposta à ação de ondas quando comparada a outras praias da região (Silva *et al*., 2011; Oliveira *et al*., 2011), por não possuir em suas adjacências, rios com elevada descarga sedimentar que contribuam para a formação de extensos bancos de areia que atenuam a energia da onda durante a maré baixa. Atualmente, esta praia está sujeita a um intenso processo erosivo resultante da forte energia hidrodinâmica local, associada ao crescente processo de ocupação que vem ocorrendo ao longo dos últimos anos em regiões de dunas, falésias e zonas de intermaré (Pinto *et al*, 2011; Pereira *et al*., 2012a).

A costa amazônica é dominada por um regime de macromarés, pois as alturas das mesmas superam 4 m de altura, segundo a classificação de Davies (1964). Este litoral difere de outras regiões do planeta, pois os processos costeiros existentes são resultantes de várias forçantes, dentre estas: presença de macromarés semi-diurnas e assimétricas, fortes correntes de marés, ondas com moderada a alta energia hidrodinâmica, descarga de dezenas de estuários que transportam para a costa uma grande quantidade de água fluvial e de sedimentos, longo período chuvoso marcado por uma elevada precipitação, incidência de fortes ventos alísios, *etc*. (Beardsley *et al*., 1995; Oliveira *et al*., 2011; Pereira *et al*., 2011; Pereira *et al*., 2012a; Pereira *et al*., 2012b).

Para melhor entender o comportamento da variação sazonal do estado morfodinâmico em uma praia amazônica sob influência de macromarés de sizígia (4-6 m) e alturas de ondas H_s, normalmente superior a 1,0 m, a praia de Atalaia foi escolhida para este estudo. Este trabalho visa avaliar a influência dos aspectos meteorológicos e hidrodinâmicos no estado morfodinâmico e balanço sedimentar da praia de Atalaia em diferentes condições: (i) *offshore* e (ii) *nearshore*. Nesta última condição foram considerados ainda os períodos de equinócio e não equinócio, a sazonalidade (seco e chuvoso) e as fases da maré (enchente e vazante).

4.3 Área de Estudo

A costa amazônica abrange os estados do Amapá, Pará e Maranhão, que juntos representam, cerca de, 35% dos 8.500 km de linha de costa brasileira. A praia de Atalaia está localizada no nordeste do estado do Pará (Figura 1), especificamente no município de Salinópolis (00º36’47’’S e 47º21’30’’W). Atalaia possui orientação W-E com 12 km de linha de costa e uma largura que varia de 200 a 400 m (Pinto *et al*., 2011). O setor oeste encontra-se ocupado por segundas residências com boa infra-estrutura ocupando áreas de falésias ativas, enquanto o setor este possui bares e restaurantes de madeira (tipo palafita) construídos sobre dunas e zona de intermaré (Sousa *et al*., 2011).

O clima na região é altamente sazonal, do tipo equatorial, quente e úmido, com duas estações principais, seca e chuvosa. A estação seca normalmente ocorre de julho a dezembro e é caracterizada por uma taxa de precipitação média de 10-15% da precipitação anual e por temperaturas médias, normalmente, entre 27 e 30°C. Por outro lado, o período chuvoso ocorre de janeiro a junho e é caracterizada por um excesso de chuvas de 1500-2500 mm, baixa insolação, baixa evaporação e temperatura mínima variando em torno de 25°C. Esta região é dominada por ventos alísios de NE (Geyer *et al*., 1996), sendo as maiores velocidades médias registradas no período seco (INMET, 2010).

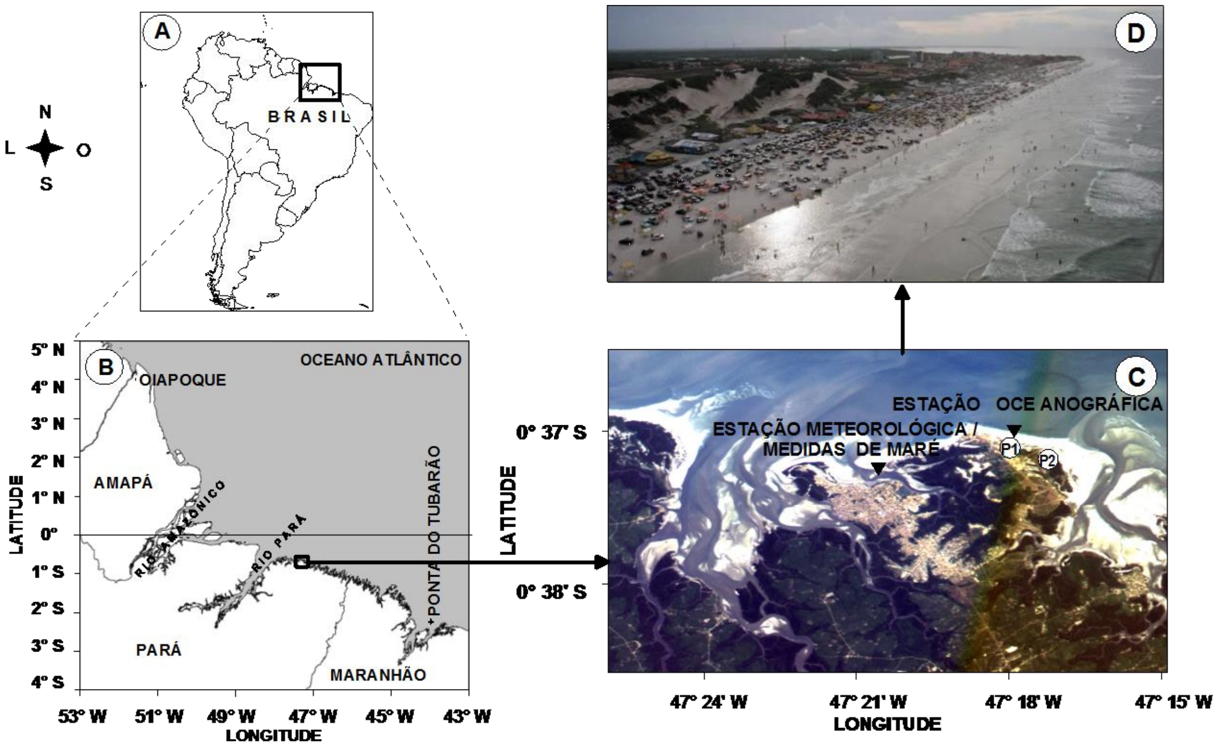


Figura 1: Localização da área de estudo: **A** - Localização geográfica do Brasil na América do Sul; **B** - Costa norte brasileira; **C** - Praia do Atalaia com a localização dos pontos de pesquisa; **D** - Vista aérea da praia do Atalaia.

4.4 Métodos

O estudo foi realizado entre novembro de 2008 e outubro de 2009, considerando duas escalas de tempo: (i) curto período, com campanhas de 25 h de duração para obtenção de dados hidrodinâmicos (*nearshore*) e topográficos, e (ii) de médio período, a partir de dados obtidos por instituições nacionais, dos quais foram adquiridos dados de climatologia e hidrodinâmica (*offshore*).

4.4.1 Climatologia e Variáveis *Offshore*

Dados de precipitação, e direção e velocidade dos ventos foram fornecidos pelo Instituto Nacional de Meteorologia - INMET (Estação de Salinópolis-A215, situado nas coordenadas 0º37’7.248’’S e 7º21’3.96’’W). Os dados foram obtidos a cada hora, entre novembro de 2008 e outubro de 2009.

Dados de ondas *offshore,* incluindo altura de onda significante (H_{os}), período (T_p) e direção (θ) foram cedidos pelo Centro de Previsão de Tempo e Estudos Climáticos (CPTEC-INPE). Os dados hidrodinâmicos (*offshore*) foram analisados diariamente, durante os quatro meses que representaram as campanhas *nearshore*.

Com os dados de ondas *offshore*, o *power* (*P*, N/ms) foi calculado, de acordo com a seguinte fórmula:

$$P = EC\mathrm{g} \quad (1)$$

onde:

E = Energia da onda (N/m²), expressa pela equação 2;

C_g = Velocidade do grupo de ondas (m/s) em águas mais profundas, expressa pela equação 3.

$$E = (\rho g H^2)/8 \quad (2)$$

$$C_g = (gT_p)/4\pi \quad (3)$$

onde:

ρ = Densidade da água (kg/m^3);

g = Aceleração gravitacional (m/s^2);

H = Altura da onda (m);

T_p = Período da onda (s).

Medidas de marés e ondas *nearshore* foram obtidas, com o auxílio de um sensor de marés e ondas (TWR 2050). Dados de correntes foram obtidos com o auxílio de um mini-correntômetro (Sensordata SD 6000). Os equipamentos foram fundeados a 3,8 m de profundidade, de acordo com o nível médio da maré (Figura 1). Dados de maré foram adquiridos a cada 2 s, com os valores médios obtidos a cada 10 minutos. Os dados de marés foram corrigidos ao nível de redução da DHN (2,75 m em Salinópolis). Medidas de correntes foram realizadas a cada 10 minutos e as direções foram representadas em relação ao norte magnético.

4.4.2 Variáveis *Nearshore*

A estação oceanográfica esteve localizada nas coordenadas 00º37'11"S e 047º21'04"W (Figura 1), para a obtenção dos dados de correntes, marés e ondas. Dois perfis topográficos foram monitorados e coletas de sedimentos foram realizadas para conhecer a variação espaço-temporal da morfologia, declividade, granulometria e o balanço sedimentar.

As coletas foram realizadas durante marés de sizígia e os meses coletados representaram:

(i) Final do período seco - baixa vazão fluvial e fortes ventos (novembro de 2008);

(ii) Período chuvoso - equinócio (março de 2009);

(iii) Final do período chuvoso - elevada vazão fluvial (junho de 2009);

(iv) Período seco - fortes ventos e equinócio (setembro de 2009).

4.4.2.1 ***Morfologia de Praia***

Dois perfis perpendiculares à linha de costa foram analisados durante os meses de estudo. Para cada perfil foram determinados pontos fixos conhecidos como E0, estando estes localizados em setores com características erosivas (P1) e relativamente estável (P2). O método topográfico utilizado foi o *Stadia* aperfeiçoado por Birkemeier (1981), que utiliza um nível automático e uma mira falante. As leituras foram realizadas, de acordo com as variações morfológicas ou a cada 20 m, quando pouca ou nenhuma variação foi detectada. Estes dados serviram para calcular o volume sedimentar, bem como a declividade da praia (graus). O balanço sedimentar foi calculado por perfil, a cada mês de campanha, sendo novembro de 2008 o mês de referência.

Simultaneamente aos trabalhos topográficos, amostras superficiais de sedimentos foram coletadas e acondicionadas em sacos plásticos devidamente etiquetados. Em laboratório, as amostras foram submetidas a processos de dessalinização e secagem em estufa a 80ºC, durante um período de 48 h. Após a secagem, 100 g da fração de sedimentos foram levados ao agitador automático com peneiras de -1.0 a 4.0 Φ durante 15 minutos, para a devida separação. Para a classificação granulométrica utilizou-se as equações propostas por Folk & Ward (1957), com o auxílio do software *Sysgran 2.4* (Camargo, 1999). Correlações foram realizadas entre as variáveis (média, mediana, assimetria, desvio padrão e curtose).

4.4.2.2 ***Análise Morfodinâmica***

As análises morfodinâmicas foram realizadas com base nos dados hidrodinâmicos e morfo-sedimentares. Para a classificação das praias em dissipativa, intermediária ou reflectiva utilizou-se a velocidade de queda adimensional-Ω (Gourlay, 1968; Dean, 1973), calculada segundo a equação 4:

$$\Omega = H_b/W_sT \qquad (4)$$

onde:

H_b = Altura significativa das ondas na arrebentação;

W_s = Velocidade de queda do grão;

T = Período da onda.

A variação relativa da maré (*RTR*) foi obtida, através da equação proposta por Davis & Hayes (1984):

$$RTR = TR/H_b \qquad (5)$$

onde:

TR = Altura da maré;

H_b = Altura da onda na zona de arrebentação;

Os resultados foram analisados considerando os seguintes dados:

(i) *Offshore* – altura da onda (H_{os}) e período correspondente (CPTEC/INPE): neste caso não foi considerado o efeito da atenuação da onda nos bancos de areia e a assimetria da maré. Os dados das marés foram da DHN (Fundeadouro de Salinópolis).

Neste caso, H_b (Eq. 6) foi calculado de acordo com Komar & Gaughan (1972):

$$H_b = 0,39g^{0,2}(TH_o^2)^{0,4} \quad (6)$$

onde:

g = Aceleração gravitacional (m/s^2);

H_b = Altura da onda (m) na zona de arrebentação;

T_p = Período da onda (s);

H_o = Altura da onda (m) *offshore*.

(ii) *Nearshore* – marés, altura modal das ondas H_s e períodos correspondentes, medidos pelos sensores de ondas e marés. Foram considerados os dados granulométricos do P1 e as condições (a) equinócio e não equinócio, bem como as fases das marés (b) enchente e vazante. Neste caso, foi considerado o efeito da atenuação da onda nos bancos de areia e a assimetria da maré.

4.5 Resultados

4.5.1 Condições Climáticas

Durante os meses estudados, os maiores índices de precipitação pluviométrica foram registrados entre janeiro e junho 2009 (período chuvoso), com um total de 1.954 mm. Em novembro 2008, setembro 2009 e outubro 2009 (estação seca) foram registrados baixos índices pluviométricos, com valores mensais inferiores a 2 mm (Figura 2).

A velocidade do vento também variou sazonalmente, e as maiores velocidades foram registradas no período seco, com valores máximos mensais de 9,3 m/s em setembro. Por outro lado, as menores intensidades mensais foram obtidas no período chuvoso, alcançando valores mínimos de 4,2 m/s em maio (Figura 3A). Quanto à direção, os ventos incidiram principalmente de NE durante a estação seca (56º < θ < 81º), com frequência de aproximadamente 99%, em novembro 2008 e setembro 2009. No entanto, março e junho além de registrarem ventos de NE em 79% e 55% do tempo, respectivamente, também apresentaram ventos incidindo de outros quadrantes (Figura 3B).

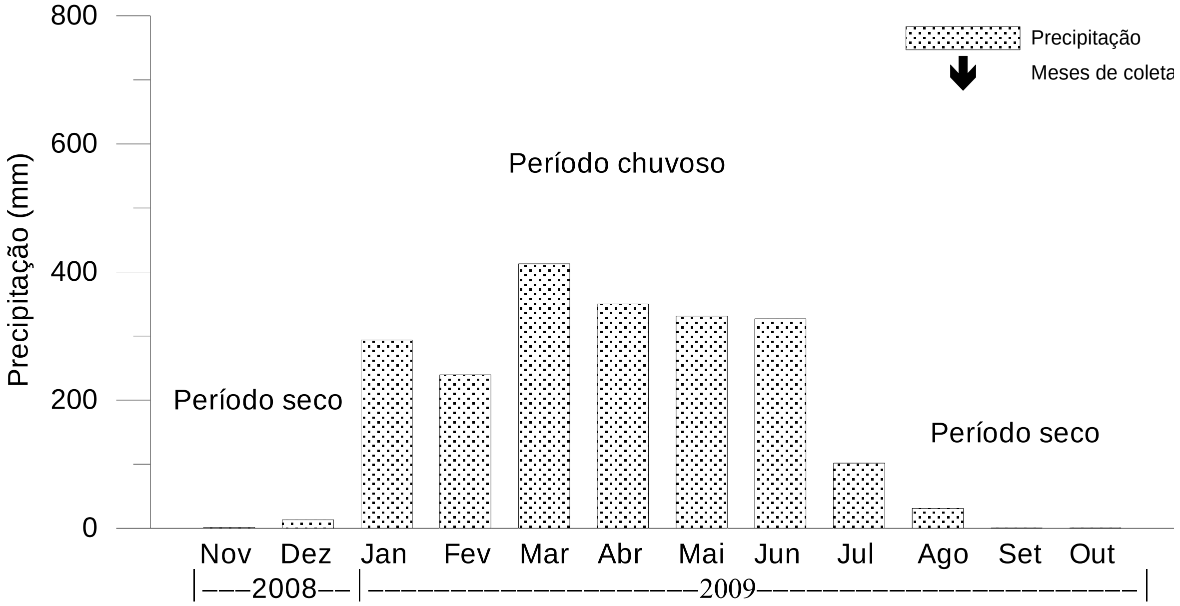
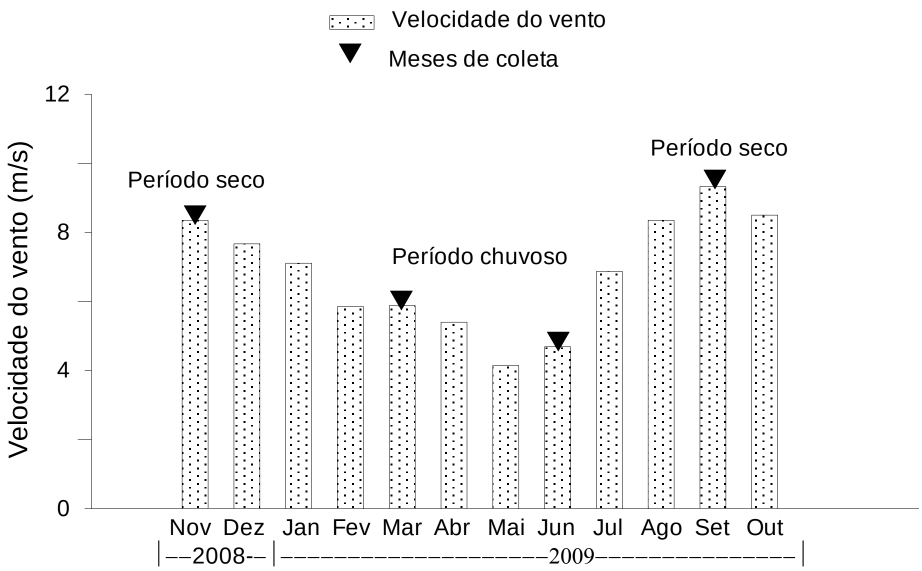


Figura 2. Precipitação mensal entre novembro de 2008 e outubro de 2009, referente à estação de Salinópolis-Pará. Fonte: INMET (estação Salinópolis).

(A)


Velocidade do vento
Meses de coleta
Velocidade do vento (m/s)
12
8
4
0
Período seco
Período chuvoso
Período seco
Nov Dez Jan Fev Mar Abr Mai Jun Jul Ago Set Out
2008
2009

(B)

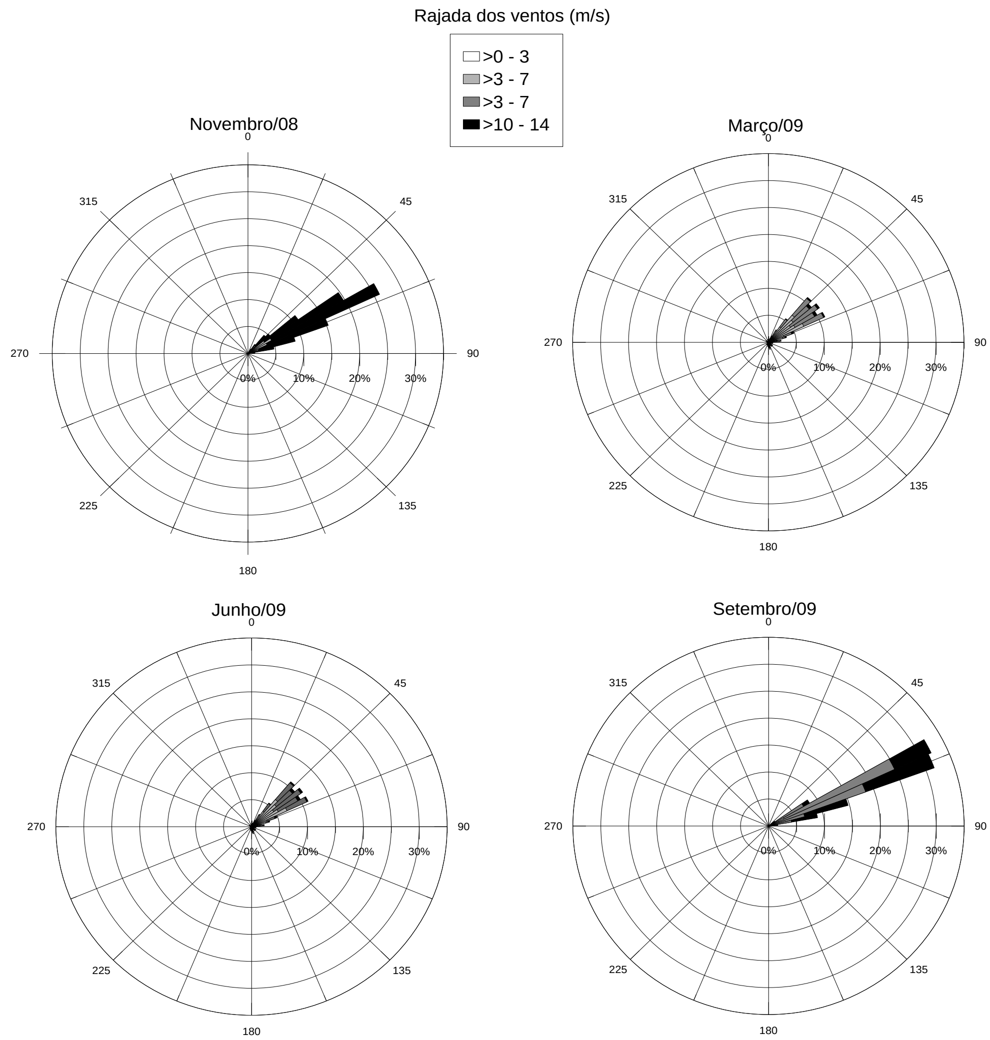

Rajada dos ventos (m/s)
>0 - 3
>3 - 7
>3 - 7
>10 - 14
Novembro/08
Março/09
Junho/09
Setembro/09
0
45
90
135
180
225
270
315
0%
10%
20%
30%

Figura 3. Intensidade dos ventos (valores máximos)-A e a freqüência de ocorrência (%) das direções-B, nas quatro condições estudadas. Fonte: INMET (estação Salinópolis).

4.5.2 Análise Hidrodinâmica

4.5.2.1 ***Condições Offshore***

Dentre as quatro condições estudadas, os períodos de equinócio (março e setembro) e fortes ventos (novembro) representaram o período de maior energia hidrodinâmica, quando comparado a junho (período de transição onde os ventos apresentaram intensidades mais baixas). No equinócio do primeiro semestre (março), os ventos sopraram principalmente entre 40° < θ < 70°N (Figuras 4 A-B), e as maiores alturas de ondas (H_{os}) variaram entre 1,1 e 1,5 m vindos de 35° < θ < 55°N (Figuras 4B-C). Estas ondas estiveram associadas a períodos mais longos (de 5 a 9s) (Figura 4D) e, consequentemente, apresentaram maiores valores de *power* entre 7000 e 16000 N/ms (Figura 4E). No equinócio do segundo semestre, os ventos sopraram mais fortes, principalmente de leste e nordeste (75° < θ < 90°N), gerando ondas vindas de 70° < θ < 80°N, com alturas entre 1 e 1,3 m (Figuras 4A-C). Estas ondas estão associadas a períodos mais curtos (de 4 a 5s) e com menores valores de *power* (entre 4500 e 8000 N/ms), quando comparadas àquelas registradas durante o equinócio do primeiro semestre (Figuras 4D-E). Em novembro, os ventos apresentaram intensidades ligeiramente mais baixas do que às registradas em setembro, gerando ondas com alturas entre 0,7 e 1,2 m, vindas entre 40° < θ < 70°N. Neste período, os períodos das ondas oscilaram entre 4 e 9s, e o *power* entre 3000 e 9000 N/ms (Figura 4). O período de menor energia de ondas (0,7 < *H*os < 1,1 m) foi observado em junho, quando a baixa intensidade dos ventos gerou ondas com baixos valores de *power* (valores inferiores a 7000 N/ms).

Com relação aos dias de coleta, os valores mais altos de H_{os} e P também foram encontrados em março, com valores respectivos de 1,21 m e 7.547,34 N/ms (Figura 4). Por outro lado, em novembro e junho foram registrados os valores mais baixos de H_{os} (1,0 e 1,08 m, respectivamente) e P (6000 e 6500 N/ms, respectivamente) (Figura 4).

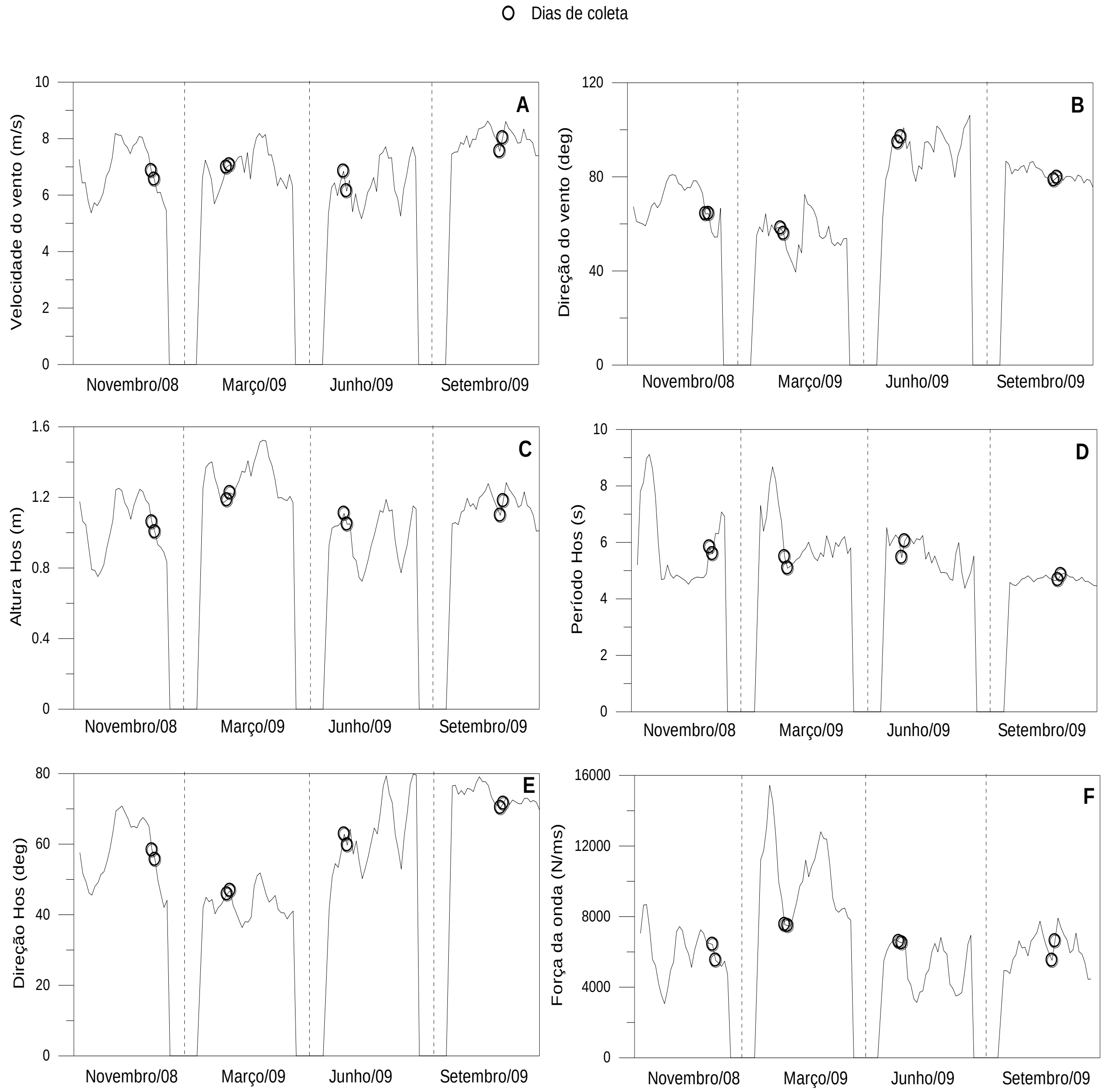


Figura 4: Variáveis *offshore*: (A) Velocidade do vento (m/s); (B) Direção do vento (deg); (C) Altura de onda significante (m); (D) Período de onda (s); (E) Direção da onda (deg) e (F) Força de onda (N/ms).

4.5.2.2 ***Condição Nearshore***

4.5.2.2.1 *Hidrodinâmica*

As marés (Figura 5A) apresentaram uma leve assimetria, com período de vazante superior ao de enchente (~6 h e 40 m vazando). As correntes de marés apresentaram um fluxo que ocorreu de SE-NW durante a enchente e de NW-SE durante a vazante (Figura 5B). As maiores alturas de marés e intensidades de correntes foram encontradas durante os equinócios de março e setembro. Neste período, a elevação da maré foi 5,0 m em março e 5,7 m em setembro (Figura 5A).

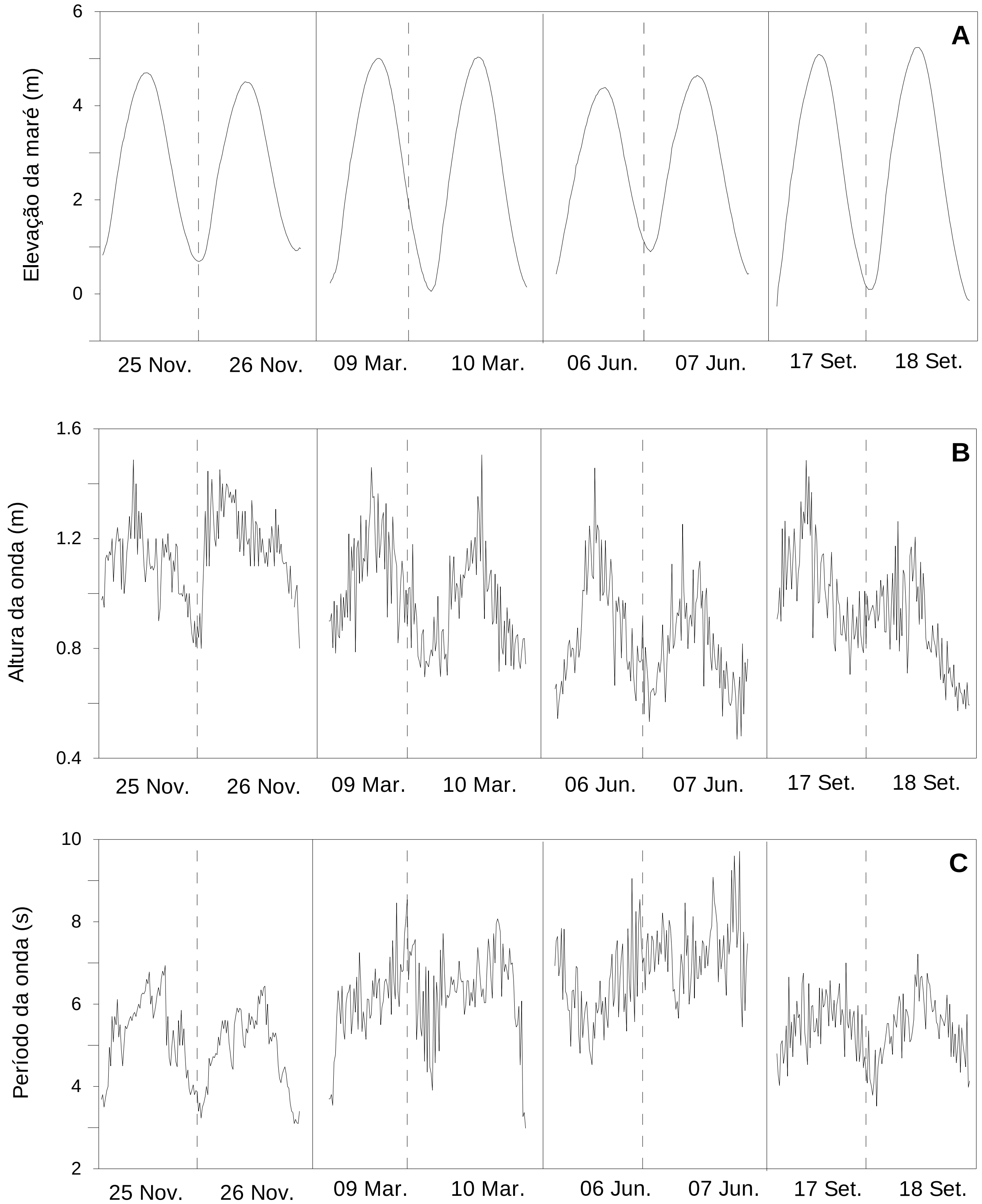


Figura 5. Variáveis *nearshore*: A – Elevação da maré (m); B – altura de onda (m); C – Período de onda (s).

Consequentemente, as maiores intensidades de correntes (Figura 5C) também foram registradas neste período, principalmente durante as enchentes (valores próximos a 0,5 m/s). Em novembro, as maiores alturas de ondas e os menores períodos (H_s = 1,1 m, T = 5s) foram registrados em decorrência dos fortes ventos locais. Neste período, as correntes de marés não foram tão evidentes quanto nos outros meses, devido à baixa vazão fluvial, os fortes ventos e a predominância das correntes de deriva em direção ao norte. Por outro lado, as menores alturas de ondas foram registradas em junho (H_s = 0,8 m, T = 6,8s) (Figuras 5D-E), coincidindo com os fracos ventos. Durante o período chuvoso, as correntes de vazante alcançaram valores máximos de 0,4 m/s. Nas quatro condições estudadas uma leve atenuação das ondas durante a maré baixa foi observada, como resultado da presença de bancos de areia.

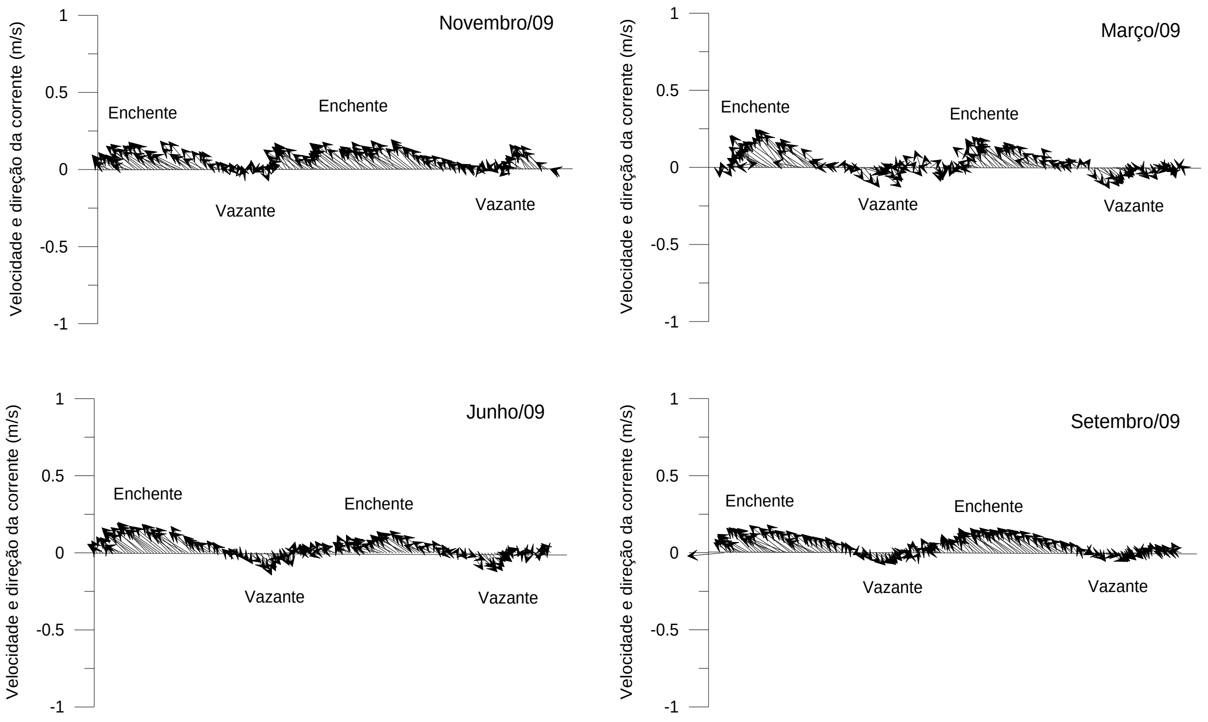


Figura 6: Variáveis *nearshore*: velocidade e direção das correntes (m/s).

4.5.2.2.2 *Análise Morfológica*

Ambos os perfis possuem baixa declividade (1º) durante a maré baixa. Com relação ao perfil superior (acima da linha média de preamar de sizígia), apenas o P1 apresentou moderada declividade (5-7º), retratando o processo erosivo predominante neste local.

O P1 possui aproximadamente 300 m, a partir do marco referencial (pós-praia) até o nível da maré baixa de sizígia (Figura 7). Este setor está situado em uma área bastante erosiva, registrando perdas de sedimentos entre novembro/08 e setembro/09 de -1,61 m³/m. Apenas entre março e junho/09 ocorreu um pequeno acréscimo de 0,49 m³/m, quando sopraram ventos de SE, contribuindo para que o setor oeste se tornasse mais protegido da incidência direta das ondas vindas do mesmo quadrante (SE), resultando em um perfil mais acrescido neste período quando comparado aos outros meses estudados (Figura 8).

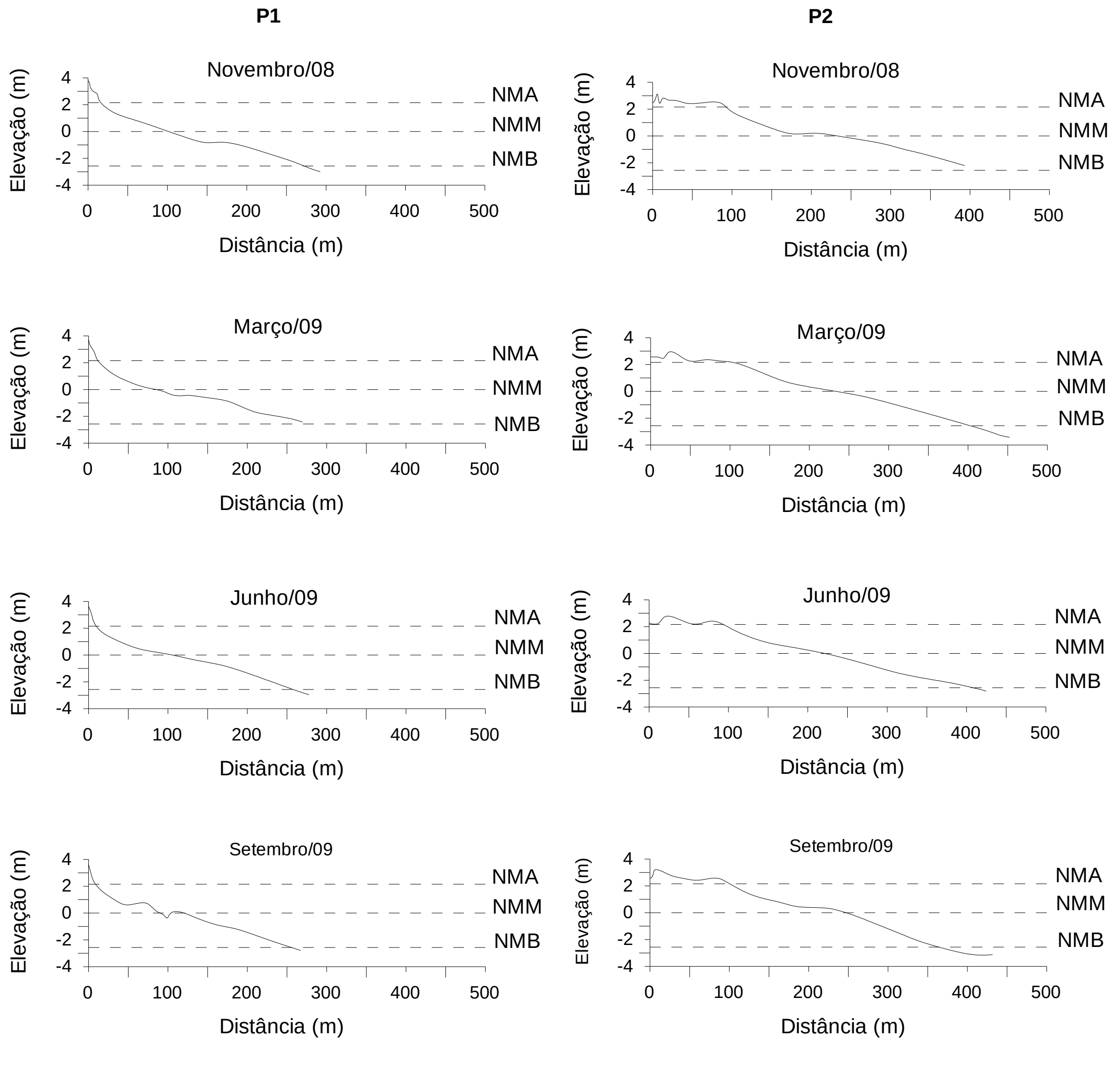


Figura 7. Perfis topográficos da praia de Atalaia (P1 e P2) demonstrando as feições morfológicas em cada mês de estudo.

O P2 é mais extenso, com cerca de 400 m, desde as dunas frontais (interrompidas por construções de madeira e rua de acesso a praia) até a linha da maré baixa de sizígia. Este perfil encontra-se na extremidade este de Atalaia. Este setor apresenta características mais estáveis (Figura 7) quando comparado ao P1. O balanço sedimentar entre novembro/08 e setembro/09 foi de -0,028 m³/m. Houve um pequeno acúmulo de sedimentos entre novembro/08 e março/09 (0,062 m³/m) e entre junho e setembro/09 (0,048 m³/m), quando os ventos sopraram de NE, fazendo com que o setor este tornasse mais protegido da incidência direta das ondas vindas de NE (Figura 8).

As dunas foram maiores no período seco, como consequência do transporte eólico, ocorrendo condições contrárias no período chuvoso, quando estas sofreram intensa erosão em decorrência da elevada precipitação pluviométrica e durante as marés equinociais, principalmente em março.

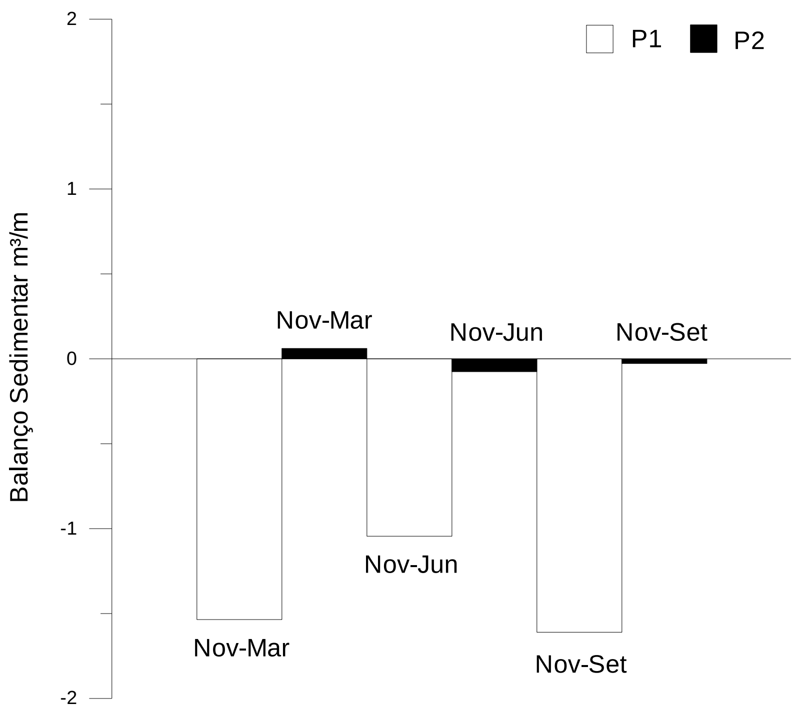


Figura 8. Balanço de sedimento (P1 e P2), tendo como referência o mês de novembro/08.

4.5.2.2.3 *Análise Granulométrica*

Houve pouca variação espaço-temporal na granulometria das amostras de sedimentos analisados. Os dados confirmam a predominância de areia fina (83%), seguidos de areia muito fina (17%), com distribuição moderadamente a bem selecionada, assimetria positiva, e curtose variando de platicúrtica a mesocúrtica. Os grãos, nos dois perfis foram ligeiramente mais finos em junho (baixa energia hidrodinâmica e período de elevada descarga fluvial) (Tabela 1).

Tabela 1: Classificação do sedimento com base no tamanho do grão e valores médios por perfil.

PERFIL1	**Nov/08**	**Mar/09**	**Jun/09**	**Set/09**	**PERFIL2**	**Nov/08**	**Mar/09**	**Jun/09**	**Set/09**
Média	2,8	2,84	2,9	2,85	Média	2,8	2,89	2,92	2,84
Mediana	2,72	2,78	2,86	2,77	Mediana	2,72	2,83	2,89	2,76
Seleção	0,58	0,58	0,63	0,6	Seleção	0,58	0,6	0,63	0,6
Assimetria	0,22	0,18	0,07	0,21	Assimetria	0,22	0,15	0,08	0,21
Curtose	0,91	0,87	0,85	0,81	Curtose	0,9	0,8	0,78	0,82

Uma análise de correlação (Figura 9), entre as características dos sedimentos mostrou uma excelente relação entre a média e mediana (R^2 = 0,9759), uma boa relação entre média e seleção (R^2 = 0,801) e média e assimetria (R^2 = 0,8178) e uma moderada relação entre média e curtose (R^2 = 0,6449). Estes resultados mostraram que uma maior predominância de areia fina (como observado em novembro, maior energia de ondas), resulta em uma melhor seleção dos grãos, e que a distribuição tende a ser positiva e mesocúrtica. Quando a percentagem de areia muito fina aumenta, como observado em junho (menor energia de ondas), a distribuição tende a ser moderadamente selecionada, assimétrica e platicúrtica.

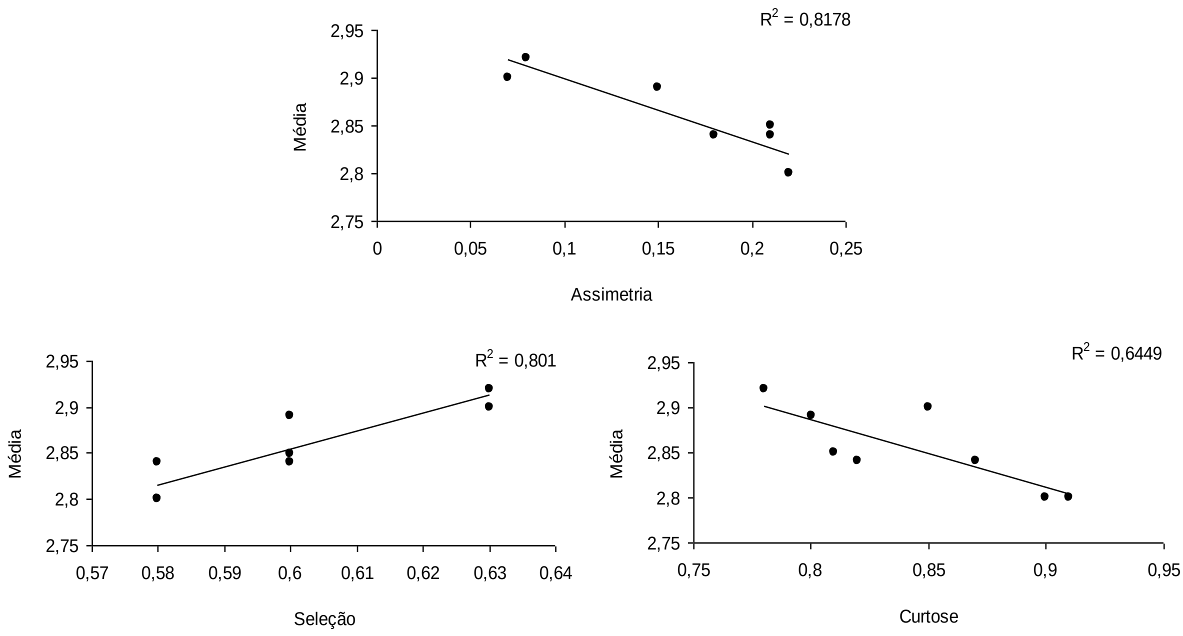


Figura 9. Correlação entre a média dos grãos e mediana (A), média e seleção (B), média e assimetria (C), e média e curtose (D).

4.5.2.2.4 *Análise Morfodinâmica*

Para a classificação morfodinâmica da praia de Atalaia, quatro diferentes condições foram analisadas. Considerando os dados *offshore* dos quatro meses de estudo, Atalaia pode ser classificada como praia dissipativa do tipo "*non barred*" (Figura 10A), com exceção do mês de junho/09 que foi classificada como "*barred dissipative".* Estas condições foram condicionadas pela alta elevação da maré nos meses de novembro, março e setembro.

Entretanto, quando os dados *nearshore* são considerados, é possível observar que o efeito da energia da onda atenuada nos bancos de areia, durante algumas fases da maré, tem contribuído para um estado morfodinâmico do tipo dissipativo, mas com característica "*non barred"* nos meses de março, junho e setembro (Figura 10B). Isto ocorre devido à maior influência da maré, quando comparada à altura das ondas (RTR, entre 3,5 e 5). Por outro lado, novembro foi classificado como dissipativa do tipo "*barred*" (Figuras 10B-C), devido às maiores alturas de ondas associadas a períodos curtos, e uma menor amplitude da maré (RTR = 2,9).

Com relação aos períodos enchente e vazante, a praia apresentou comportamento similar, com característica dissipativa do tipo "*non barred"* durante a maré enchente e vazante, exceto em novembro que foi classificado como dissipativo do tipo "*barred*".

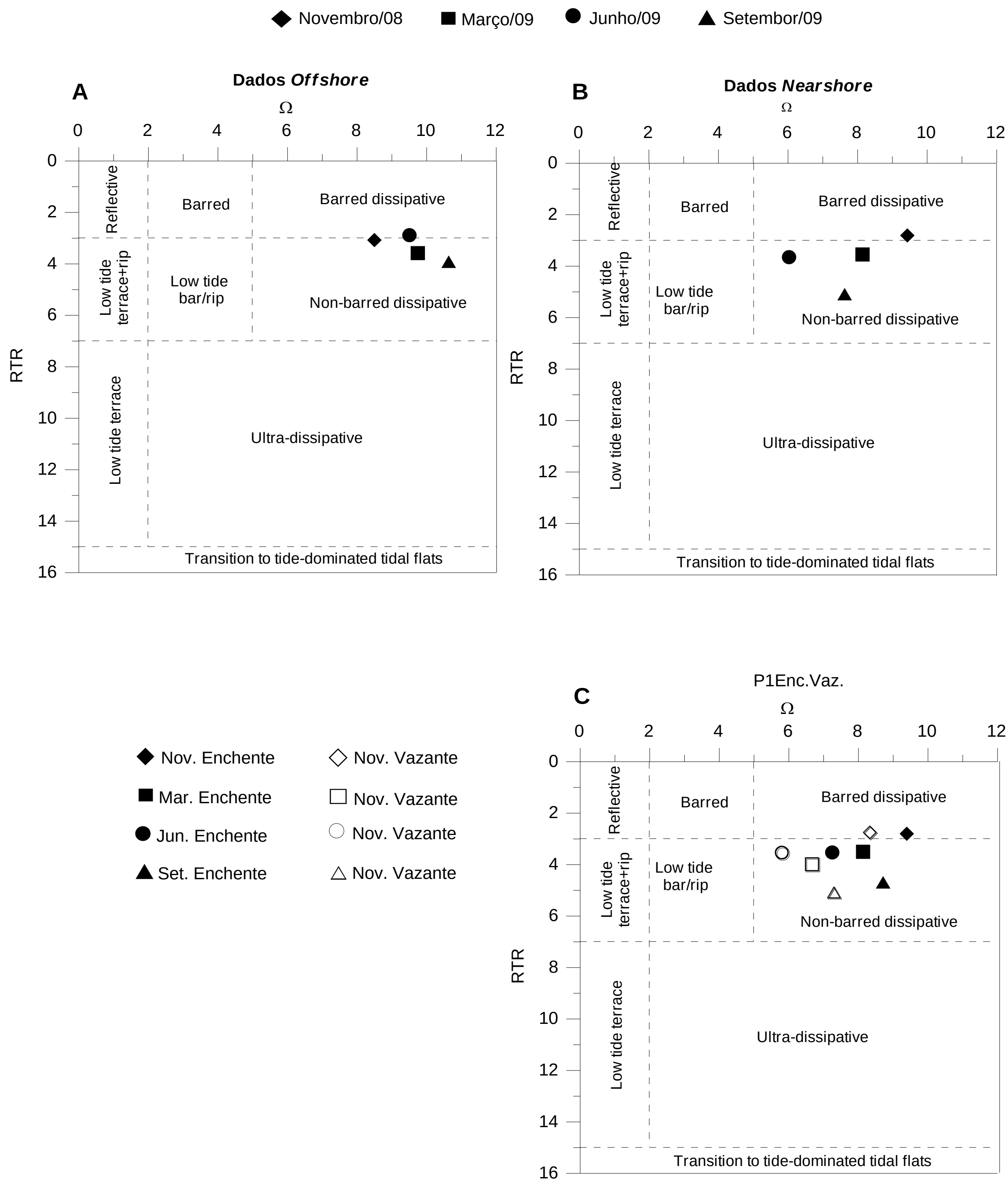


Figura 10: Valores de RTR e Ω de acordo com as condições (A) *offshore,* (B) *nearshore* e (C) perfil 1 durante os períodos de enchente e vazante da maré.

4.6 Discussão

Este setor amazônico possui um clima sazonal representado por uma estação seca e outra chuvosa. O principal fator que causa as chuvas nesta região é o deslocamento da Zona de Convergência Intertropical (ZCIT) em direção ao estado do Amapá, Pará e Maranhão (Figueroa & Nobleman, 1990). A migração da ZCIT também é responsável pela sazonalidade do comportamento dos ventos, sendo as menores velocidades registradas durante a estação chuvosa e as maiores durante a estação seca (INMET, 2009).

As marés são assimétricas, com maiores velocidades de correntes registradas durante a maré enchente. Tais condições já foram estudadas por outros autores em algumas praias da região (Pereira *et al*., 2009; Monteiro *et al*., 2009; Oliveira *et al*., 2011; Pinto *et al*., 2011). Segundo Mazda *et al*. (2002) e Lam-Hoia *et al*. (2006) padrões assimétricos da maré são consequências da configuração morfológica da zona costeira e da plataforma continental adjacente, além disso, a presença de uma vasta floresta de manguezais recortada por furos, canais, rios e estuários são fatores que influenciam significativamente na assimetria da maré na região.

Eventos de alta energia foram proporcionados pelas marés equinociais de sizígia nos meses de março e setembro/09. Os ventos influenciaram no clima de ondas *nearshore*, e ondas com alturas maiores e períodos mais curtos foram observadas quando estes sopraram com maiores intensidades (novembro/08 e setembro/09). Condições similares foram também observadas por Monteiro *et al*. (2009) na praia de Ajuruteua, Pereira *et al*. (2011) em praias de São Luis, Jackson & Nordstrom (1992) em praias estuarinas de *New Jersey*, Eliot *et al.* (2006) em praias australianas e Hartmann *et al.* (2009) em praias do Mediterrâneo. Por outro lado, ondas com menores alturas e períodos mais longos ocorreram quando os ventos apresentaram menores velocidades (estação chuvosa), o que provavelmente contribuiu para a formação de um perfil de praia mais plano, como observado em junho.

Próximo a Atalaia não existem rios de grande porte e o suprimento de sedimentos fluviais é reduzido quando comparado a outras praias da região, em que é possível observar extensos bancos de areia que atenuam a energia das ondas durante os períodos de baixa-mar. Este fato tem proporcionado a este ambiente, condições de moderada a alta energia de ondas tanto no período da preamar, quanto durante a baixa-mar. Estas condições já diferem daquelas observadas em outras praias amazônicas, onde próximo desembocam estuários de moderada descarga de sedimentos, como por exemplo, a praia de Ajuruteua (Monteiro *et al*., 2009) e Princesa (Pereira *et al*., 2012).

De uma forma geral, a morfologia praial segue um padrão em resposta às mudanças do clima de ondas e altura das marés (Poate *et al*., 2009; Trindade & Ramo-Pereira, 2009), variando temporalmente e espacialmente (Medina *et al*., 1994). O perfil 1 tendeu a perdas subsequentes de sedimentos durante a maior parte do estudo. Este setor também é afetado pela ocupação tanto na zona de intermaré, que apresenta construções de madeira, quanto no campo de dunas, que se encontra sob forte pressão imobiliária (presença de hotéis, pousadas e segundas residências). O perfil superior foi o mais afetado com o escarpamento das dunas durante as marés equinociais de sizígia. Eventos de alta energia são responsáveis por acentuadas mudanças morfológicas de caráter erosivo como foi observado por Jackson *et al*. (2002), Vila-Concejo (2010), Strauss *et al*. (2009), Sénéchal *et al*. (2009). Durante o período de transição (baixa energia hidrodinâmica), não houve erosão significativa, o que explica a suave deposição observada no mês de junho (P1).

Com relação ao P2, a orientação da linha de costa W-E e a predominância de ondas vindas de NE são fatores importantes para que neste setor, as ondas alcancem à linha de praia, com uma menor energia (refração). Próximos ao P2, bancos de areia situados na adjacência da desembocadura do estuário do rio Sampaio, possivelmente também auxiliam na atenuação da energia da onda (Figura 1), propiciando a ocorrência de um perfil mais estável, mesmo durante os períodos de equinócio. Processos erosivos, neste setor, foram observados durante períodos de baixa energia (junho), mas quando os ventos sopraram de SE.

Masselink & Short (1993) relatam que mesmo em ambiente com maior alcance da maré, as ondas permanecem sendo um grande contribuidor para mudanças temporais no perfil de praia. Porém, com o aumento do alcance da maré, a energia da onda tende a se dissipar por uma vasta zona de intermaré e a taxa de transporte sedimentar e as consequentes mudanças no perfil tornam-se menores (Wright *et al*., 1985). Segundo Vila-Concejo *et al*. (2010), processos erosivos ocorrem em partes mais vulneráveis da praia sob condições de alta energia. Isto explica a erosão recorrente no P1 durante a maior parte do estudo. Além deste perfil está exposto à alta energia hidrodinâmica, ainda encontra-se sob forte pressão antrópica. Problemas erosivos relacionados a níveis acelerados de ocupação humana em regiões de dunas e intermarés já foram estudados em outras áreas costeiras apresentando uma influência negativa nestes ambientes (French, 2001; Pereira *et al*., 2007b; Silva *et al*., 2009; Pereira *et al*., 2011). Para Mwakumania & Bdo (2007), processos físicos quando associados às atividades antrópicas afetam negativamente tanto os processos hidrodinâmicos quanto morfodinâmicos na costa.

Com relação ao estado morfodinâmico, Atalaia apresentou características de praia dissipativa na maioria das condições estudadas, apresentando uma zona de intermaré de moderada declividade, com sedimentos finos a muito finos e ondas de moderada a alta energia com períodos curtos, tal como estudado por outros autores (Masselink & short, 1993; Short, 2003; Short, 2006).

A assimetria da maré e a atenuação das ondas durante parte da vazante, baixa-mar e parte da enchente têm contribuído para classificações diferenciadas entre as condições *nearshore e offshore*, em Atalaia. De uma forma geral, a praia foi classificada como dissipativa do tipo *"non barred",* entretanto a alta energia das ondas em novembro (*nearshore*) contribuiu para que a praia fosse classificada como dissipativa do tipo *"barred"*. Por outro lado, as condições *offshore* em junho (RTR = 2,9) contribuíram para que a praia também fosse classificada como dissipativa do tipo *"barred"*.

4.7 Considerações Finais

A praia de Atalaia apresentou variações sazonais nos padrões hidrodinâmicos e morfológicos. Eventos de alta energia foram proporcionados pelas marés equinociais de sizígia nos meses de março e setembro/09 e pelos fortes ventos de nordeste no período seco, causando erosão no P1 e acresção no P2. Comportamento oposto (acresção P1 e erosão P2) foi observado durante períodos de baixa energia. Tais fatores naturais, quando associados à ocupação inadequada em campos de dunas e zonas de intermarés têm contribuído substancialmente para a intensificação dos processos erosivos locais.

Em geral, Atalaia apresentou características de praia dissipativa (baixa declividade composta por areia fina a muito fina), sob influencia de macromarés e ondas de moderada energia hidrodinâmica. Atalaia foi classificada como "*non-barred dissipative*", na maioria dos meses estudados e o modelo proposto por Masselink & Short (1993) parece não ser ideal para praias sob influencia de rios com elevada descarga fluvial que formam barras e atenuam a energia das ondas, na qual a energia das ondas é modulada pela presença de bancos de areia durante algumas fases da maré.

Medidas de caráter preventivo são necessárias para amenizar os problemas erosivos e preservar as belezas naturais que ainda existem neste ambiente. Por esta razão, estudos em uma maior escala de tempo são importantes para uma melhor compreensão da dinâmica costeira da praia de Atalaia.

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CAPÍTULO V

5. Considerações Finais

Os resultados obtidos neste estudo mostram que as condições climáticas e hidrológicas foram os principais responsáveis pelas flutuações na turbidez da água, oxigênio dissolvido, nutrientes dissolvidos e concentrações de clorofila-*a*. O despejo de esgoto doméstico não tratado resultou na contaminação bacteriológica, embora este ambiente apresente uma rápida circulação das águas devido à alta energia hidrodinâmica, o que limitou a contaminação por coliformes termotolerantes. Esta alta energia hidrodinâmica, principalmente durante as marés equinociais de sizígia, associada à falta de planejamento urbano levaram a problemas adicionais, tais como erosão costeira.

Eventos de alta energia foram proporcionados pelas marés equinociais de sizígia nos meses de março e setembro/09 e pelos fortes ventos de nordeste no período seco. Durante estes períodos foi possível registrar erosão no P1 e acresção no P2. Por outro lado, durante períodos de baixa energia, acresção foi observado no P1 e erosão P2. Tais comportamentos também estão relacionados à orientação da linha de costa e à incidência da propagação das ondas. A ocupação inadequada em campos de dunas e zonas de intermarés tem contribuído substancialmente para a intensificação dos processos erosivos locais.

Em geral, Atalaia apresentou características de praia dissipativa com baixa declividade composta por areia fina a muito fina,ondas de moderada energia e extensa zona de *surf*. Desta forma, Atalaia foi classificada como uma praia modificada por maré com estado morfodinâmico do tipo "*non-barred dissipative*", na maioria dos meses estudados.

Contudo, medidas emergenciais de caráter preventivo são necessárias para amenizar os problemas erosivos e preservar as riquezas naturais que ainda existem neste ambiente. Por esta razão, estudos em uma maior escala de tempo são importantes para uma melhor compreensão da dinâmica costeira da praia do Atalaia.

Assim, as seguintes medidas são sugeridas para evitar maiores impactos no ambiente local:

(i) Implementação de um sistema de saneamento público;

(ii) Remover as fossas da zona de intermaré e região de dunas, a fim de evitar maiores contaminações da água subterrânea e costeira;

(iii) Fazer o monitoramento contínuo da qualidade da água e outras variáveis (como, físicas, ecológicas e sociais) da zona costeira;

(iv) Implementar um criterioso planejamento urbano para minimizar as pressões sobre os ambientes costeiros.

De acordo com este trabalho, as características ambientais das praias amazônicas são muito diferentes de outras praias brasileiras. Com isso, critérios de avaliações específicas sobre os aspectos ambientais precisam ser re-definidos para esta região e mais estudos em outras praias amazônicas são também necessários para determinar o limite de valores apropriados para as variáveis hidrológicas com relação à escolha dos padrões adequados para a qualidade da água para recreação. É necessário também estabelecer novos critérios de classificação do estado morfodinâmico para as praias amazônicas que estão sob influencia de macromarés e ondas de moderada energia modulada por bancos de areia.

ANEXO

Primeira página do artigo publicado e do artigo aceito para publicação na Revista *Journal of Coastal Research*

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Effects of the lack of coastal planning on water quality and land use on a macrotidal beach (Atalaia, Pará) in the Amazon Region

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ABSTRACT

Pinto, K.S.T., Pereira, L.C.C., Vila-Concejo, A., Gorayeb, A., Sousa, R.C. de and Costa, R.M. da, 2011. Effects of the lack of coastal planning on water quality and land use on a macrotidal beach (Atalaia, Pará) in the Amazon Region. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 1401 - 1405. Szczecin, Poland, ISSN 0749-0208

The conservation and management of the coastal zone of the Amazon region demands special attention, given the richness of its natural resources. The aim of the present study was to evaluate the impact of natural events and human activities on Atalaia beach, and to develop guidelines for the implementation of coastal management programs. Data were collected between November, 2008, and November, 2010. Four sets of variables were assessed: (i) physical variables (climatology and hydrodynamics), (ii) hydrological variables (water temperature, salinity, pH, turbidity, dissolved oxygen and nutrients, chlorophyll-*a*, and thermotolerant coliform levels), (iii) urban development and (iv) spatial distribution of services and infrastructure. The results indicate that climate and hydrodynamical conditions were the main factors responsible for fluctuations in water salinity, turbidity, dissolved oxygen, dissolved nutrients, and chlorophyll-*a* concentrations. The discharge of untreated domestic sewage was responsible for bacteriological contamination, although the rapid turnover of the high-energy hydrodynamic environment limited contamination by thermotolerant coliforms. This high hydrodynamic energy, primarily during the equinoctial spring tides, and the lack of urban planning, nevertheless generates other problems, such as coastal erosion. The following measures were recommended: (i) rationalize sewage disposal; (ii) removal of cesspits from the intertidal zone and dunes to avoid contact with groundwater and tides; (iii) implementation of a public sanitation system; (iv) continuous monitoring of water quality for the control of bathing areas, and (v) stricter urban planning and regulation to minimize pressures on coastal environments.

ADITIONAL INDEX WORDS: *Equatorial beach, coastal management, human impact on beaches.*

INTRODUCTION

Coastal zones encompass complex natural environments that are vulnerable to the rapid urbanization and economic development that has taken place during the twentieth century (Cicin-Sain and Knecht, 1998; Irtem *et al*., 2005). These locations are prime areas for residential, commercial, industrial and harbor development (Carrero *et al*., 2009; Schlacher and Thompson, 2008). As a consequence, human activities have placed increasing pressure on coastal environments, including the (i) loss of habitats such as mangroves, reefs, dunes, and lagoons, (ii) increasing production of solid waste, (iii) decrease in water quality, and (iv) loss of infrastructure through erosion. The growing demand for services and infrastructure, and the increasing output of waste can not only affect the quality of beach water, but may even alter the natural features that attract beachgoers (Breton *et al*., 1996; Crawford, 2007; Pereira *et al*., 2007a; Mohanty *et al*., 2008; Ten Voorde, 2009). Beaches appear to be among the most vulnerable coastal environments, due primarily to their attractiveness as a site for leisure activities, and the development of related economic activities (Bauer and Sherman, 1999).

The conservation and management of the coastal zone of the Amazon region – which includes the Brazilian states of Amapá, Maranhão, and Pará – demands special attention, given the richness of its natural resources and its unique configuration, immense tropical and mangrove forests, and the enormous output of freshwater and sediments from its river system (Meade *et al*., 1985; Geyer *et al*., 1996). Studies of the region's oceanographic processes are still rare, and effective management of the coastal zone is an enormous challenge for local governments (Szlafsztein and Sterr, 2007). In addition, the Pará State Coastal Management Program (GERCO-PA) has been relatively unsuccessful in comparison with similar programs in other Brazilian states.

The coastal zone of Pará can be divided into three geomorphologically-distinct sectors: (i) Atlantic coast; (ii) mainland estuary, and (iii) estuary islands. Due to its natural characteristics, the Atlantic coast is the most popular for recreational activities. In order to evaluate the effects of these activities in the context of the absence of adequate local planning for the regulation of land use and the control of water quality, the present study focused on the Atlantic coast beach of Atalaia, the most popular resort of this sector. This equatorial sandy beach receives relatively large numbers of beachgoers, especially during July which in the area is the touristic high season. The aim of the present study was to evaluate the impact of human activities on the characteristics of the beach in the context of its unique natural attributes, and to contribute to the development of guidelines for the implementation of effective coastal management programs.

STUDY AREA

Atalaia beach (Figure 1) is located in the municipality of Salinópolis in northeastern Pará, 220 km from the state capital, Belém, and 13 km from the center of Salinópolis. Urban development is based on the tourism industry, which is essential to the local economy (Szlafsztein, 2005).

This 12 km-long dissipative beach is formed by elongated sandy ridges 200-400 m wide (low-high spring tide water levels) with a west-east orientation, surrounded by dunes, lagoons, and mangroves. Local tides are semidiurnal, with spring tide heights up to 5.5 m (DHN, 2010). Incident waves are normally from the northeast, with significant heights (Hs) between 0.4 and 1.3 m (CPTEC, 2010). The local climate is classified as Amw' in the Köppen system, and has two distinct seasons, a wet season, normally between January and June and a dry season, from July to December (INMET, 2010).

In terms of land occupation, the beach has two distinct sectors: an east sector occupied mainly by simple wooden structures (bars, beach houses, and guest houses) on the dunes and intertidal zone, and a west sector dominated by private beach houses, mansions, and hotels, which extends much further inland.

METHODS

Data were collected between November, 2008, and November, 2010. Four types of variables were analyzed: (i) physical variables (winds, precipitation, currents, waves, and tides), (ii) hydrological variables (water temperature, salinity, pH, turbidity, and concentrations of dissolved oxygen, nutrients, chlorophyll-*a*, and thermotolerant coliforms), (iii) urban development, and (iv) spatial distribution of services and infrastructure.

Meteorological data (rainfall and wind) were obtained from the National Meteorological Institute between November, 2008 and October, 2009. Four campaigns of over 25 hours were conducted in November, 2008, March, 2009, June, 2009 and September, 2009. Hydrodynamic and hydrological data were obtained during spring tide periods. A mini-current meter, CTD (salinity and temperature), and wave and tide data loggers were bottom mounted at a depth of 1.7 m in the subtidal zone and programmed to collect mean data every 10 minutes.

For the measurement of hydrological data (pH, turbidity, dissolved oxygen and nutrients, chlorophyll-*a* and thermotolerant coliforms), samples of subsurface water were obtained every 3 hours using Niskin oceanographic bottles. In the laboratory, the samples were analyzed according to the procedures of Strickland and Parsons (1968) for dissolved oxygen, Strickland and Parsons (1972) and Grasshoff *et al.* (1983) for dissolved nutrients and

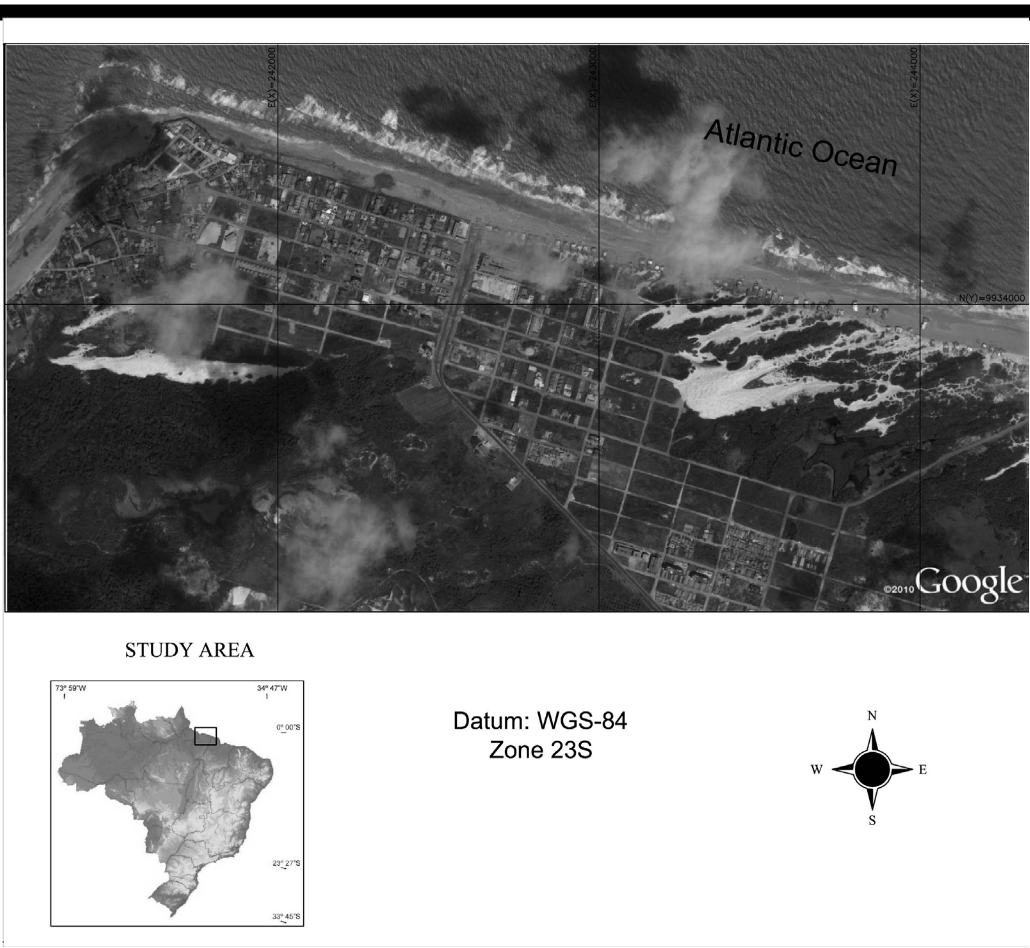

Figure 1. Location of the study area.

chlorophyll-*a*, and APHA (2004) for thermotolerant coliforms. Turbidity and pH were also measured in the laboratory. All the buildings on the waterfront were identified and georeferenced using a GPS in November, 2010.

RESULTS

Physical Variables

The highest monthly mean air temperatures (> 28°C) and wind speeds (> 3.5 m/s) and lowest precipitation levels (< 1 mm) were recorded during the dry season. Conversely, the highest monthly mean precipitation (> 300 mm) with the lowest temperatures (< 26.5°C) and wind speeds (< 2.3 m/s) were recorded during the wet season.

Local tides were semidiurnal and weakly asymmetric (flood tide up to 6:40 h in duration), with heights of up to 5.5 m during equinoctial spring tide events. Currents were mostly tidal with predominant northwest direction during the flood tide, and southeast direction during the ebb tide. Highest current speeds were recorded during the flood tide (maximal of 0.5 m/s in March and September), while maximal speeds of 0.4 m/s were registered during the ebb tide (March and June). Wave energy was modulated by the low tide due to wave attenuation on sand banks and during strong winds, Hs attained 1.5 m (November, 2008).

Water Quality

The lowest salinity (5.7 psu), temperature (27.4°C), dissolved oxygen (5.92 mg/l) and pH (7.42) were all recorded in the wet season, as were the highest turbidity (up to 118 UT) and the highest concentrations of dissolved nutrient (phosphate: 0.6 µmol/l; silicate: 329.7 µmol/l), and the lowest chlorophyll-*a* (5.2 mg/m³) concentrations. Conversely, the highest salinity (up to 37.4 psu), temperature (29°C), pH (up to 8.68), chlorophyll-*a* (82 mg/m³) and the lowest dissolved nutrient concentrations (nitrite: 2.36 µmol/l, nitrate: 24.34 µmol/l) and turbidity (9.01 UT) were recorded in the dry season. High concentrations of thermotolerant coliforms (> 1,100 MNP/100ml) were recorded only during equinoctial spring tide events (March and September), when the abnormally high tides reached the level of the cesspits located in the intertidal zone.

Urban Development

The east sector of the Atalaia waterfront is occupied mainly by simple wooden structures (guest houses, bars, and beach houses) built on the dunes or intertidal zone. This zone concentrates the highest number of beachgoers. In the west sector, the houses are built on a region strongly affected by erosive processes. This has led to the construction of sea walls and other protective structures (Figure 2A, B). In the east sector, by contrast, the wooden structures are transferred to new locations within the dunes whenever threatened by erosive processes.

Due to the lack of a public sanitation system or refuse collection, sewage and solid waste are deposited directly onto the beach. This study registered 50 cesspits and more than 15 sewage outlets along the beach (Figures 2C, D). Atalaia also lacks public water supply, and electricity supplies and street cleaning are intermittent. Vehicles are driven onto the beach and parked in the intertidal zone (Figures 2E-2G).

The infrastructure of the waterfront includes 86 bars, 50 private houses, and five guest houses, 25 lamp posts, 7 garbage dumpsters, four public telephones, one car-park, a few shops, and one ATM. With the exception of the main access road, streets are no more than sandy tracks.

As Atalaia is considered to be the state's best beach, the east sector tends to get overcrowded during the peak vacation period (July), especially during weekends. The intense traffic in the intertidal zone during this period leads to crashes and other accidents (Figure 2G). There is also considerable increase in sewage discharge and the disposal of solid waste, including plastics, paper and metal, food leftovers, and human and animal excrement (Figure 2D, H).

DISCUSSION

The high water turbidity, chlorophyll-*a*, dissolved oxygen and nutrient concentrations registered throughout the year, as well as low salinity in the rainiest months are a consequence of the local natural conditions (for example, climate, hydrodynamical pattern and geomorphological features). A series of factors, including the macrotidal regime, strong tidal currents, northeasterly trade winds, high rainfall rates, substantial fluvial discharge, the irregular shape of the coastline (with countless estuaries and bays), and the presence of mangrove systems (Meade *et al*., 1985; Marengo, 1995; Kineke *et al*., 1996; Santos *et al*., 2008) are the main responsible by control the hydrological variables in the studied area.

The unregulated occupation of the coastline and the lack of a public sanitation system appear to be the primary factors determining the bacteriological quality of the coastal waters. The high tides, mainly in March and September, reach the level of the cesspits located in the intertidal zone, contributing to the increasing of the bacteriological levels during the high tide period. However, the high hydrodynamic energy results in a rapid turnover and renovation of the water, which reduces contamination and the risks to public health. Similar results were obtained by Silva *et al*. (2009) at four urban beaches in São Luís (Maranhão state) where 101 outlets discharged sewage directly onto the beaches. Pereira *et al*. (2007a) have shown that, in more sheltered beaches, the water turnover is greatly reduced and bacteriological contaminations from sewage outlets may have considerable impacts on public health.

The lack of adequate traffic infrastructure is also a serious problem on many Amazonian beaches (Pereira *et al*., 2006; Silva *et al*., 2009), causing both intrinsic problems such as traffic jams and accidents, and environmental impacts. At Atalaia, the high concentration of vehicles also contributes to the overcrowding of the intertidal zone (Sousa *et al*., in this issue).

Morphodynamic studies are urgent in this Amazon sector to know the local volumetric evolution. Studies made by Souza-Filho *et al*., 2003; Alves and El-Robrini, 2006; Pereira *et al*., 2007b; Monteiro *et al*., 2009, Pereira *et al*., 2009 and Szlafsztein and Sterr, 2007 - in other beaches located in northeastern Pará - showed that hydrodynamical, hydrographical and geomorphological characteristics associated to the unregulated construction of buildings in that coastal zone are the main factors responsible for the observed erosive processes.

The urban development of coastal areas creates problems throughout the World. Studies in Spain (Breton *et al*., 1996), India (Mohanty *et al*., 2008) and North Carolina (Crawford, 2007) have shown that the pattern of occupation of the coastal zone is determined primarily by local legislation. The occupation of dunes, cliffs, the intertidal zone or mangroves is prohibited by both Brazilian federal law number 7661 of May 16th, 1988, and by Pará state legislation (law number 5587/95). At Atalaia, illegal occupation of these areas, together with a lack of infrastructure and services, has negative implications for natural resources and consequently, for the local tourism industry, a situation repeated at a number of sites on the coast of Pará.

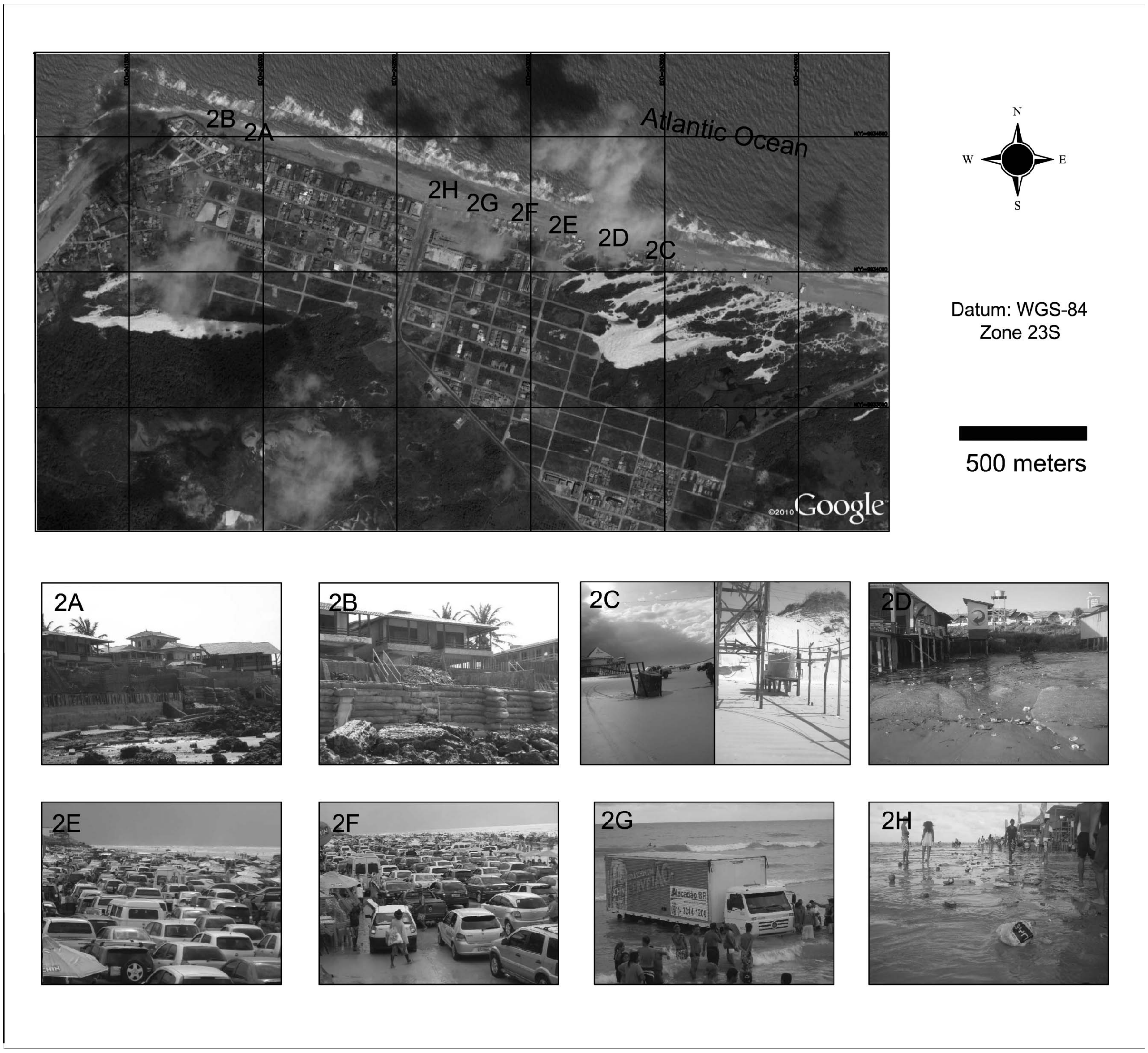

Figure 2. General conditions recorded in Atalaia beach.

Coastal management in Brazil is regulated by federal law 7661, which instituted the National Coastal Management Plan (PNGC). In Pará, the state program (GERCO-PA) has had only limited success. Szlafsztein (2009) found a lack of interest on the part of public administrators or reduced priority for coastal environments, combined with a relative deficiency of financial resources and personnel, considering the size of the area. The results of the present study indicate a clear and urgent need for the implementation of a coastal management program within the Salinopólis area, which should involve local inhabitants, the scientific community, government agencies, and NGOs.

FINAL CONSIDERATIONS

The results of the study indicate that climatic and hydrological conditions were the main factors responsible for fluctuations in water turbidity, dissolved oxygen and nutrients, and chlorophyll-*a* concentrations. The discharge of untreated domestic sewage was responsible for bacteriological contamination, although the rapid turnover of this high-energy hydrodynamic environment limits contamination by thermotolerant coliforms. This high hydrodynamic energy, primarily during the equinoctial spring tides, and the lack of urban planning generates additional problems, such as coastal erosion. The following measures are required to avoid further impacts on the local environment: (i) rationalize sewage disposal; (ii) removal of cesspits from the intertidal zone and dunes to avoid contact with groundwater and tides; (iii) urgent implantation of a public sanitation system; (iv) continuous monitoring of water quality and other variables (physical, ecological and social) of the coastal zone, in particular for the control of bathing areas, and (v) stricter urban planning and regulation to minimize pressures on coastal environments.

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Oceanographic Conditions and Human Factors on the Water Quality at an Amazon Macrotidal Beach

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ABSTRACT

PEREIRA, L.C.C.; PINTO, K.S.T.; DA COSTA, K.G.; VILA-CONCEJO, A., and DA COSTA, R.M., 0000. Oceanographic conditions and human factors on the water quality at an Amazon macrotidal beach. *Journal of Coastal Research,* 00(0), 000–000. West Palm Beach (Florida), ISSN 0749-0208.

Atalaia beach is situated in the NE of the Brazilian state of Pará and is one of the most popular with tourists and local beachgoers. This paper describes the seasonal variation in the meteorologic and oceanographic characteristics of the study area, as well as the effects of the lack of a public sanitation system on the quality of the water used by beachgoers. Oceanographic campaigns were carried out between November 2008 and September 2009. The study area is characterized by high rainfall rates (>1900 mm during the rainy season), NE winds with mean speeds of up to 4.36 m/s in the dry season and 3.06 m/s in rainy season, macrotidal conditions (tidal range >4.0 m), moderate tidal current speeds (up to 0.5 m/s), and significant wave heights up to 1.5 m. Water temperature was relatively homogeneous (27.6°C to 29.3°C). Salinity varied from 5.7 (June) to 37.4 psu (November). The water was well oxygenated (up to 9.17 mg/L), turbid (up to 118 nephelometric turbidity units), alkaline (up to 8.68), and eutrophic (maximum of 2.36 μmol/L for nitrite, 24.34 μmol/L for nitrate, 0.6 μmol/L for phosphate, and 329.7 μmol/L for silicate), and it presented high concentrations of chlorophyll *a* (up to 82 mg/m^3). The natural conditions observed in the present study indicate the need for a review of the hydrologic criteria used for the evaluation of beaches by national and international agencies and their adaptation to the reality of the Amazon Coast. The lack of a public sanitation system has led to bacteriologic contamination and the loss of water quality.

ADDITIONAL INDEX WORDS: *Natural conditions, anthropogenic activities, sewage, coastal zone, Amazon.*

INTRODUCTION

Coastal zones encompass a variety of environments, many of which have been coming under growing pressure from ongoing urbanization and economic development. In recent years, the number and variety of human activities has been increasing progressively. In addition to the exploitation of natural resources and recreational use, there is increasing pollution from industrial and residential development (Lau, 2005; Small and Nicholls, 2003; Steffy and Kilham, 2006).

The Amazon Coast encompasses the littoral zones of the Brazilian states of Amapá, Pará, and Maranhão, which together represent just over one-third of the country's 8500 km coastline. This region includes one of the world's largest continuous tracts of mangrove forest (Lara, 2003) and is dominated by the discharge of numerous rivers, including the Amazon River, the world's largest by water volume.

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Hydrodynamic patterns in this region are controlled by a series of factors, including the macrotidal regime, strong tidal currents, northeasterly trade winds, lack of Coriolis forces, high rainfall rates, and major fluvial discharge (Kineke *et al.*, 1996; Marengo, 1995; Meade *et al.*, 1985). Topographic features are also important: the continental shelf is both extensive and gently sloping, and the coastline is highly irregular, with innumerable bays, estuaries, and mangrove systems criss-crossed with tidal creeks (Nittrouer and DeMaster, 1986; Silva, Souza-Filho, and Rodrigues, 2009).

The coast of the northeastern portion of the state of Pará is typical of this scenario (Figure 1). The region is relatively densely populated, with 27% of the state's total population (IBGE, 2010), and local areas of the coastal zone have been impacted considerably by human activities over the past few decades (Gorayeb, Lombardo, and Periera, 2009; Guimarães *et al.,* 2009, Pereira *et al.,* 2007, 2010; Souza-Filho, Martins, and Costa, 2006; Szlafsztein and Sterr, 2007).

Within this region, Atalaia has become one of the state's most popular beaches, which has resulted in increasingly intense development and occupation of the coastal zone in recent years, although this growth has not been accompanied by any

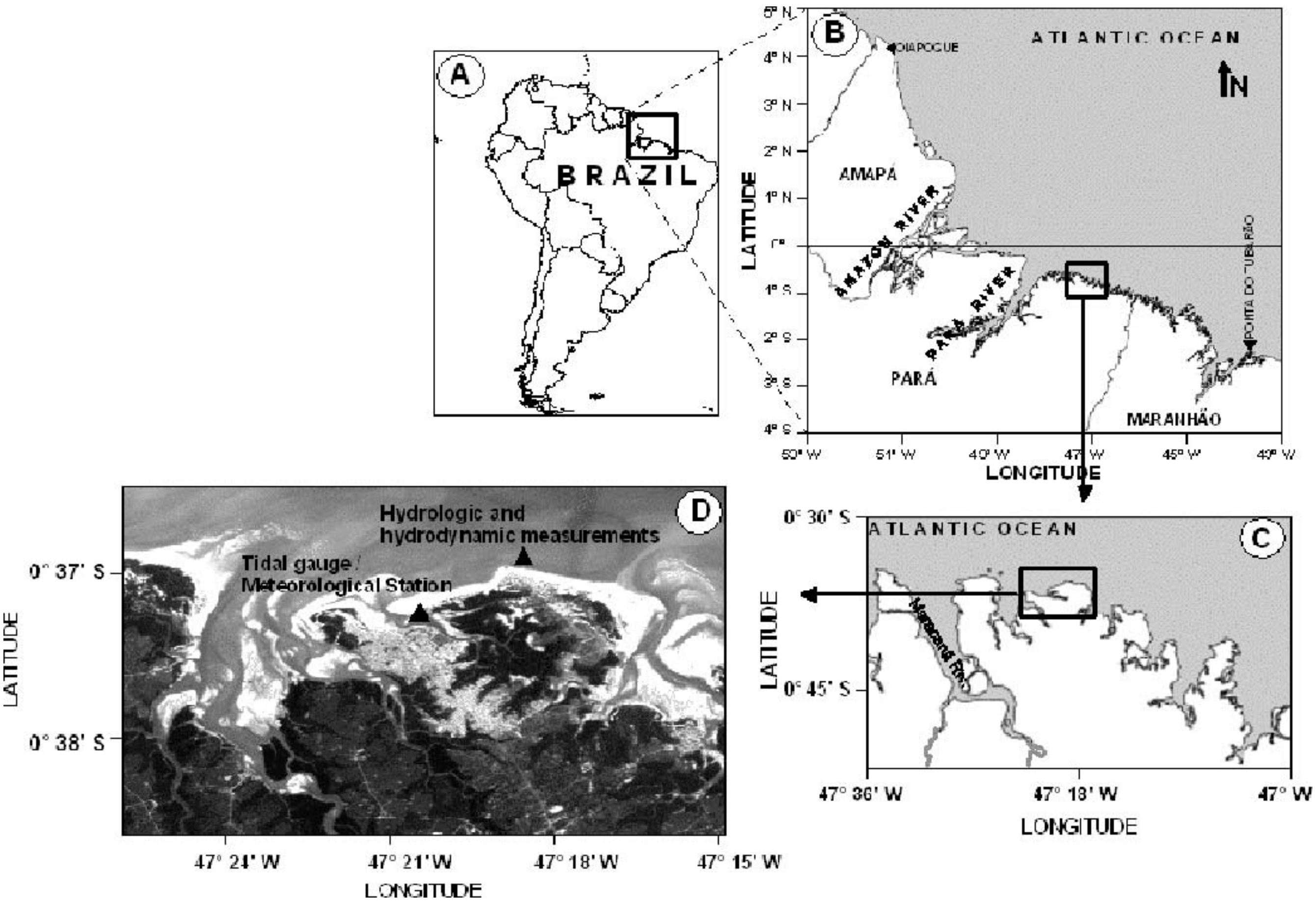

Figure 1. Study area: (A) South America, (B) Brazilian Amazon coastal zone, (C) part of the Pará state, and (D) Atalaia beach showing hydrodynamic and hydrologic station, and tidal gauge and meteorologic stations.

adequate development of the public sanitation system, and sewage discharge onto the beach affects the quality of the water used for recreational activities (*i.e.,* bathing, water sports). However, natural conditions, such as the region's massive fluvial discharge and high hydrodynamic energy, are responsible for the characteristics of its water, including high turbidity and pH and dissolved oxygen and nutrient concentrations, as well as its low salinity during rainy season. This suggests that the criteria of organizations such as the National Environment Council (CONAMA) and the Blue Flag Program need to be carefully reassessed and redefined for application to the evaluation of beaches on the Amazon Coast. In this context, the present paper aimed to evaluate the effects of seasonal fluctuations in meteorologic and hydrodynamic conditions on hydrologic and microbiological (thermotolerant coliform) variables. In addition, the implications of the lack of a public sanitation system for the quality of the water were analyzed.

STUDY AREA

The study focused on the Praia de Atalaia, a beach on Atalaia Island in the municipality of Salinópolis, in the northeastern extreme of the Brazilian state of Pará (Figure 1). Salinópolis has a population of 39,180, and tourism is an important sector of the local economy (IBGE, 2010; PARATUR, 2010). Atalaia is very popular with local beachgoers and tourists, especially during the high season (July). However, the beach is a relatively long distance from the state capital and other major cities, and this, together with the prolonged and intense rainy season, has tended to limit development of the local tourist industry.

The beach is 12 km long and 200–400 m wide (low–high spring tide water levels). This macrotidal dissipative beach is bordered by the Atlantic Ocean to the north and east and by dune fields, mangroves, and buildings (bars, restaurants, houses, and hotels). There is no public sanitation system, and cesspits in the intertidal zone are a potential threat to the quality of the beach's water, especially in terms of bacterial contamination.

Tides are semidiurnal, with spring tide heights of up to 5.5 m (DHN, 2010). Data from the Weather Forecasting and Climatic Studies Center of the Brazilian Space Agency (CPTEC, 2010) show that prevailing offshore waves come from the NE, with significant wave heights (*Hos*), normally between 0.4 and 1.3 m.

The local climate is classified as Amw′ in the Köppen system and is characterized by two distinct seasons (rainy and dry).

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Only 10–15% of the annual precipitation falls during the dry season (normally from July to December), when mean temperatures are between 27°C and 30°C. The rainy season (January to June) is characterized by high precipitation rates (1500–2500 mm) low insolation and evaporation, and temperatures as low as 25°C. The area is dominated by northeasterly trade winds (Geyer *et al.*, 1996), and the highest average wind speeds are normally recorded during the dry season (INMET, 2010).

METHODS

The present study was based on two complementary approaches. Hydrodynamic and hydrologic data were collected in four campaigns of 25 hours' duration between November 2008, and September 2009, distributed in such as way as to best sample seasonal differences, but during the tourist off season. The November 2009 sample represents the period of lowest fluvial discharge during the dry season, while that of March 2009 coincides with rising discharge during the rainy season, and June 2009 coincides with the period of highest fluvial discharge during the rainy season. Finally, September 2009, represents the dry season period of decreasing fluvial discharge. The second approach involved the analysis of the meteorologic and hydrodynamic data collected daily by the respective Brazilian monitoring institutions during the same period.

Meteorologic data (wind speed, wind direction, and rainfall) were obtained from the Brazilian Institute of Meteorology's Salinópolis-A215 station (0°37′7.248″ S, 47°21′3.96″ W). Offshore wave data (*Hos* and direction) were obtained from the Weather Forecasting and Climatic Studies Center of the Brazilian Space Agency (CPTEC-INPE) in order to contextualize the measurements obtained during the monthly campaigns.

The field campaigns were conducted at the spring tide during periods when few beachgoers were present. A mooring was mounted on the seafloor (1.7 m depth at low spring tide) at 00°37′11″ S, 047°21′04″ W (Figure 1), with a Sensordata SD 6000 minicurrent meter, a conductivity–temperature–depth recorder (CTD; XR-420, RBR), and a tide and wave recorder (TWR 2050) attached. Tidal currents were measured every 10 minutes, and their direction was recorded relative to the magnetic north. Waves were measured at a rate of 4 Hz (512 samples per 10 min). Tide data were acquired every 2 seconds, with mean values being obtained every 10 minutes.

Subsurface water samples were collected using a Niskin oceanographic bottle every 3 hours in the surf zone. In the laboratory, turbidity and pH were measured using a turbidity meter and pH meter, respectively. The procedure of Strickland and Parsons (1968) was used for the measurement of dissolved oxygen; the procedures of Strickland and Parsons (1972) and Grasshoff, Emrhardt, and Kremling (1983) were used for dissolved nutrients; and the procedure of Strickland and Parsons (1972) was used for chlorophyll a, while thermotolerant coliform levels were measured using the method of the American Public Health Association (APHA 2005).

For statistical analyses, the assumptions of normality and homogeneity of variance were investigated using the Lilliefors test (Conover, 1971) and Bartlett's Chi square (Sokal and Rohlf, 1969) run in the Statistica 6.0 package (StatSoft, 2001). When data were not normal, log $(x + 1)$ transformations were conducted to provide near-normal distributions using version 6.1.6 of the Plymouth Routines Multivariate Ecological Research (PRIMER) statistical package (Clarke and Warwick, 1994). A one-way analysis of variance, followed by Fisher's least significant difference *post hoc* test were used to analyze monthly and seasonal fluctuations in physical, chemical, and microbiologic variables. However, when the variances were heterogeneous, the nonparametric Mann-Whitney *U* test or the Kruskal-Wallis test was used to investigate possible differences between months and seasons (Zar, 1999).

RESULTS

Climate

A total of 1954 mm of precipitation was recorded in the study area during the rainy season, *i.e.,* between January and June 2009 (Figure 2A). March was the rainiest month, with a total of 412.8 mm. By contrast, only 146.8 mm was recorded in the dry season months of November and December 2008, and July–September 2009. The overall mean air temperature was 27.2°C, with monthly values varying from 25.95°C in May to 28.90°C in September (Figure 2A).

Wind speeds also varied seasonally (Figure 2B), with relatively strong winds (mean speed between 2.84 and 4.36 m/s, and maximum from 6.87 to 9.33 m/s) blowing from the NE during the dry season (Figure 2C). During the rainy season, winds were weaker, blowing from the NE, NW, SE, and SW (Figure 2C), with mean monthly speeds between 1.40 and 3.06 m/s and maximum speeds from 4.15 to 7.11 m/s (Figure 2B).

Hydrodynamic aspects

Tidal currents run predominantly NW during the flood tide and SE during the ebb tide (Figure 3). Highest current speeds were recorded in March and September, reaching a maximum of 0.5 m/s during the flood tide. In March and June (rainiest months), the ebb tide currents reached a maximal of 0.4 m/s.

The tidal cycle was weakly asymmetric (Figure 4), with the ebb tide lasting up to 6 hours 40 minutes. High tides reached between 3.9 and 5.3 m, with the highest tides recorded during the equinoctial spring tides of March and September.

Wave energy was modulated by the low tide due to wave attenuation on sand banks (Figure 4). Maximum wave height (*Hs*) values (0.8–1.5 m) were recorded in November, and the lowest were recorded in June (generally lower than 1.2 m). Offshore wave data from CPTEC-INPE (Figure 5) indicated a predominance of waves from the NE during the study period. November, March, and September had higher-energy offshore wave conditions, with *Hos* values generally above 1 m. June was characterized by much lower-energy wave conditions ($Hos < 1$ m).

Hydrology aspects

Average water temperature ranged from 27.6°C to 29.3°C during the study period, with the highest values being recorded during the dry season, when insolation was at its highest. There was substantial diurnal variation, with the highest

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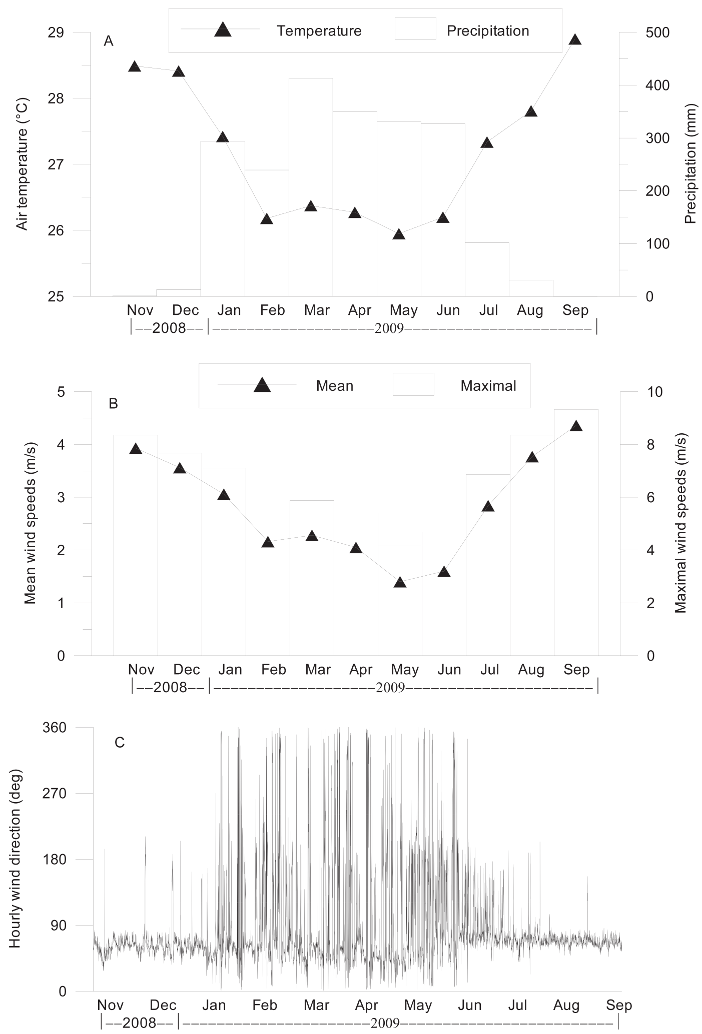

Figure 2. Climate data for the study area, obtained from Instituto Nacional de Meteorologia's Salinópolis-A215 station.

temperatures occurring between 1200 and 1800 hours, and the lowest from 0000 to 6000 hours (Figure 6). Salinity was highest in November, when rainfall and fluvial discharge were lowest, with values between 34.6 and 37.4 psu. Salinity was lowest in June (5.7–8.8 psu), the rainy season month characterized by the highest fluvial discharge (Figure 6).

Dissolved oxygen concentrations (Figure 7A) were highest in September (7.6–9.17 mg/L), presumably reflecting the relatively strong tidal currents and winds of this period, while these were lowest in March (5.92–7.31 mg/L). Monthly (F = 25.874; $p = 0.000$) and seasonal (F = 10.661; $p = 0.002$) values were significantly higher during the dry season.

A similar, but inverse pattern was recorded for turbidity, which was highest in the rainy season (U = 90.00; $p = 0.022$) and in particular during June ($H = 26.27$; $p = 0.000$). Turbidity was lowest during November (period of least rainfall and lowest fluvial discharge) ranging between 9.01 and 14.83 nephelometric turbidity units (NTU). As mentioned above, the highest values were recorded in June (flood tide, 25.56 NTU; ebb tide, 118 NTU), coinciding with the period of greatest fluvial discharge, with the highest values recorded during the ebb tides (influence of the fluvial discharges) (Figure 7B).

Significant monthly (F = 16.405; $p = 0.000$) and seasonal (F = 44.387; $p = 0.000$) variation was also observed in pH, with the higher values (8.12–8.68) being recorded in November, a period of low rainfall and high salinity. The lowest pH values (7.42–8.00) were recorded in the rainy season months of March and June (high rainfall and low salinity) (Figure 7C).

Chlorophyll a concentrations (Figure 7D) varied significantly among months (H = 32.84; $p = 0.000$) but not between seasons. While the highest values were recorded in November (42.4–82.0 mg/m^3), the lowest were observed in June and September (5.2–16.7 mg/m^3), coinciding with the lowest and highest turbidity values, respectively.

As for chlorophyll a, dissolved nutrient concentrations varied significantly among months (nitrite, H = 32.89; $p = 0.000$; nitrate, H = 32.84; $p = 0.000$; phosphate, H = 32.85; $p = 0.000$; silicate, H = 20.64; $p = 0.000$) but not between seasons. The

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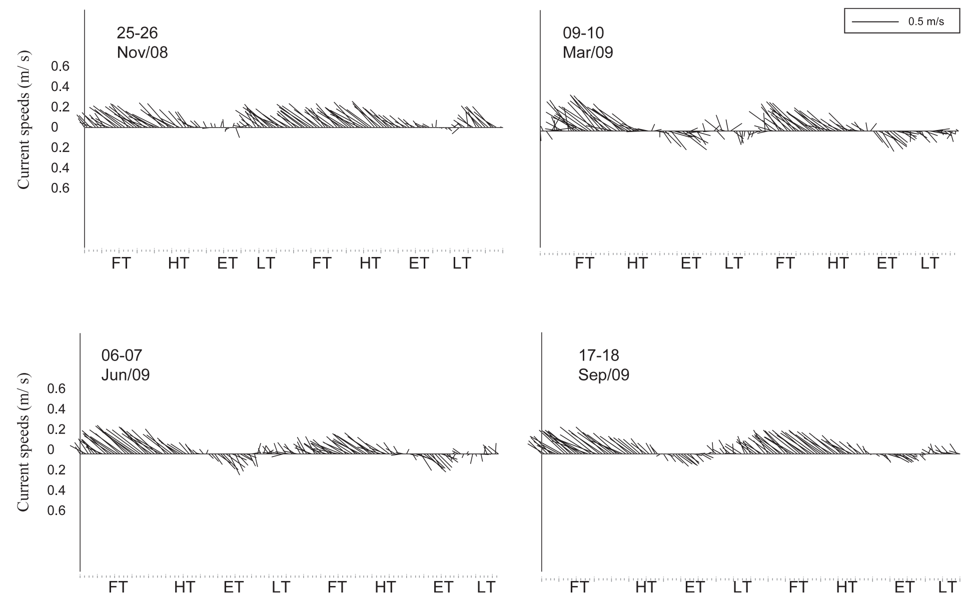

Figure 3. Coastal current speed (m/s) and direction at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

highest nitrite concentrations (1.49–2.36 μmol/L) were recorded in September (equinoctial spring tide), whereas the lowest values (0.16–0.17 μmol/L) were obtained in November (Figure 7E), coinciding with the highest concentrations of chlorophyll *a*. Nitrate concentrations were also relatively high in September (2.50–24.34 μmol/L), while the lowest values were observed in November and March (Figure 7F), once again coinciding with increased chlorophyll *a*. By contrast, the lowest phosphate (0.15–0.36 μmol/L) and silicate (11.5–45.0 μmol/L) concentrations were recorded in March, while they were highest in June (phosphate, 0.35–0.60 μmol/L; silicate, 186.0–329.7 μmol/L), presumably reflecting the high fluvial discharge during this period (Figure 7G/H).

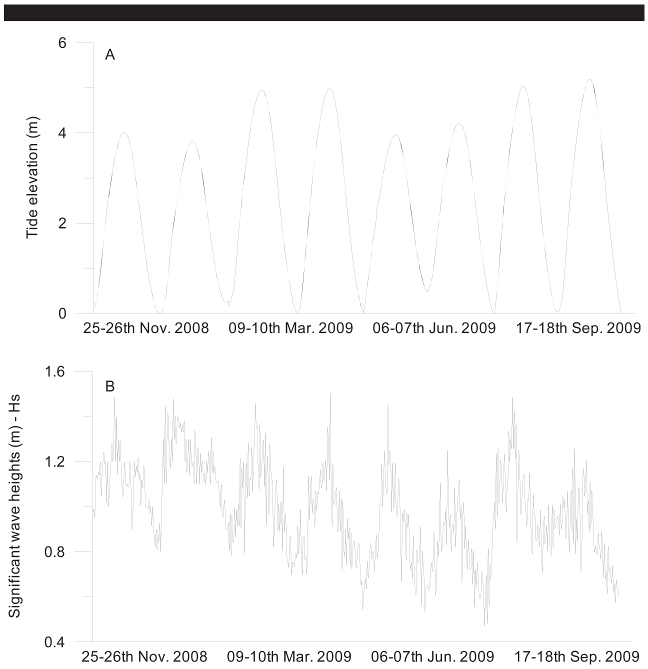

Figure 4. Tide ranges (m) and significant wave heights (m) recorded at Atalaia beach during the studied period.

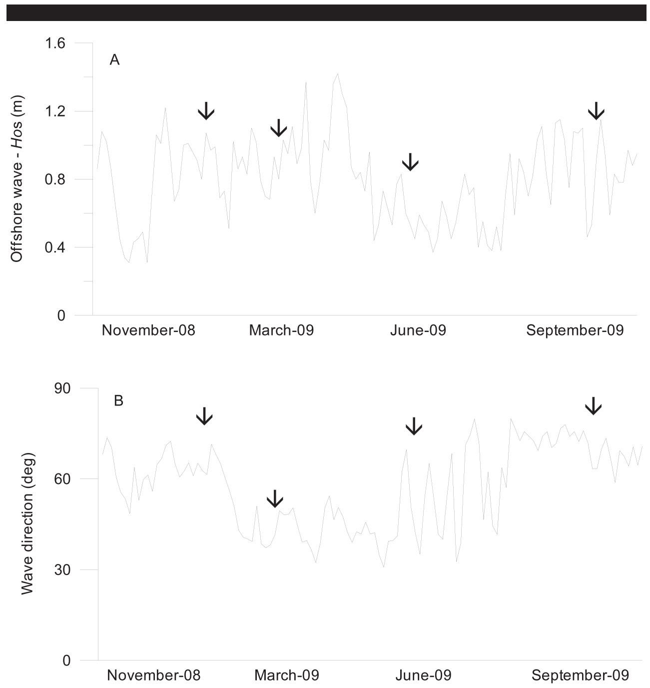

Figure 5. Offshore wave data. The arrows (↑) indicate the days on which data were collected in the present study.

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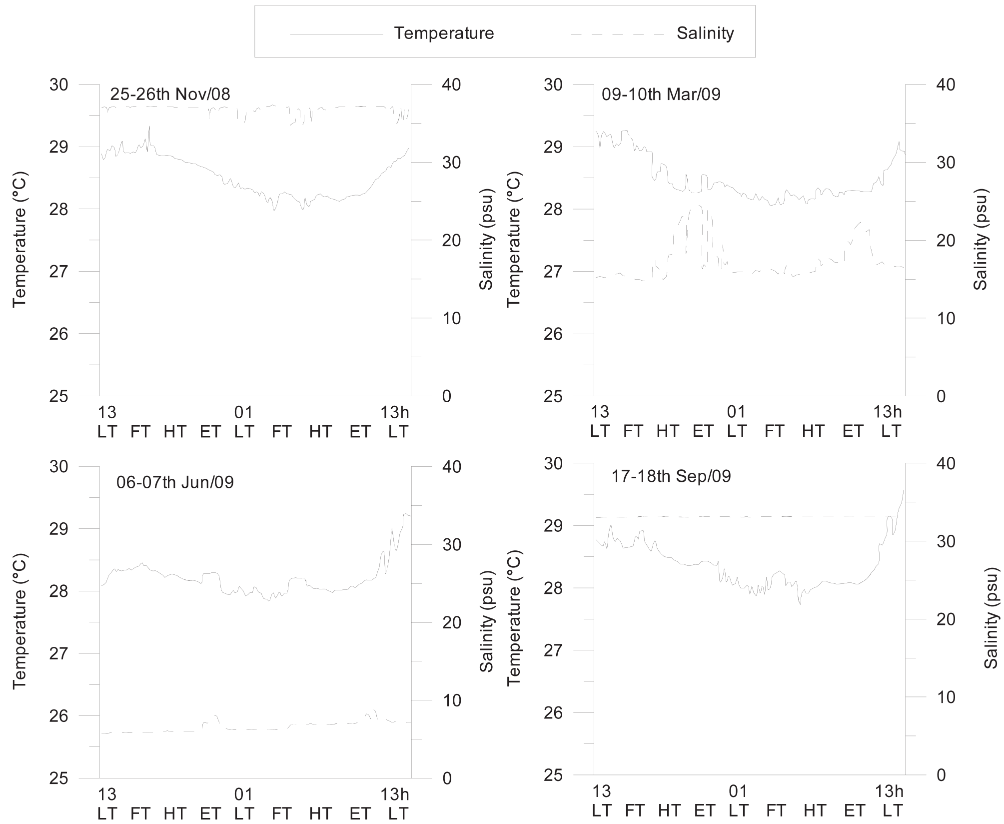

Figure 6. Water temperature (°C) and salinity (psu) at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

Around a third of samples analyzed presented concentrations of thermotolerant coliforms above 1100 most probable number (MPN)/100 ml. Concentrations were highest in March and September (Figure 8), when the equinoctial spring tides reached the level of the cesspits constructed in the intertidal zone. A recent observation recorded 50 cesspits and at least 15 sewage outflows within the study area (Figure 9). Thermotolerant coliform concentrations varied significantly among months ($F = 3.9095$; $p = 0.01739$), but not between seasons.

DISCUSSION

Physical processes and water quality

Atalaia beach presents two distinct seasons, with high precipitation rates in the first half of the year and a marked dry period in the second half. Similar seasonal patterns have been recorded over the long term (23-y data series) for Pará as a whole (Moraes *et al.,* 2005). The Intertropical Convergence Zone (ITCZ) is one of the main determinants of climatic patterns in this equatorial region. In the first semester, it moves to the Southern Hemisphere, resulting in an increase in precipitation and a reduction in temperature. During the second semester, the ITCZ moves northward, provoking a reduction in precipitation rates and an increase in air temperatures (Figueroa and Nobre, 1990; Marengo, 1995). Wind speeds also increase during this period, while more moderate speeds are typical of the rainy season, except for occasional strong gusts (Martorano *et al.,* 1993; SEPOF, 2008).

The study area is dominated by macrotidal conditions with strong tidal currents and low to moderate significant wave heights (*Hs*). Nearshore and offshore wave conditions showed similar patterns. The highest hydrodynamic energy conditions were recorded in November, and during the equinoctial months of March and September, when both tides and waves attained their greatest heights, and coastal currents were strongest. By contrast, the lowest-energy hydrodynamic conditions were recorded in June, when the lowest wind speeds, wave heights, tidal range, and current speeds were recorded.

Within the study area, the orientation of the coast associated with the typical northeasterly winds enhanced the propagation of waves, although tidal asymmetry is less pronounced than that at other sites on the Amazon Coast. This may be related to the fact that Atalaia is located within an area of lower fluvial sediment input, which reduces the potential for the formation of sandbanks or long-shore bars, allowing the flood tide to reach the beach quickly, rather than being trapped in these features, as observed at the nearby Ajuruteua beach (Monteiro, Pereira, and Oliveira, 2009), where the extensive sandbars formed by the Caeté River contribute to a much stronger asymmetry, with an ebb tide of around 7 hours 30 minutes during the spring tides.

The highly seasonal climate and associated variation in hydrodynamic conditions combined to determine the observed

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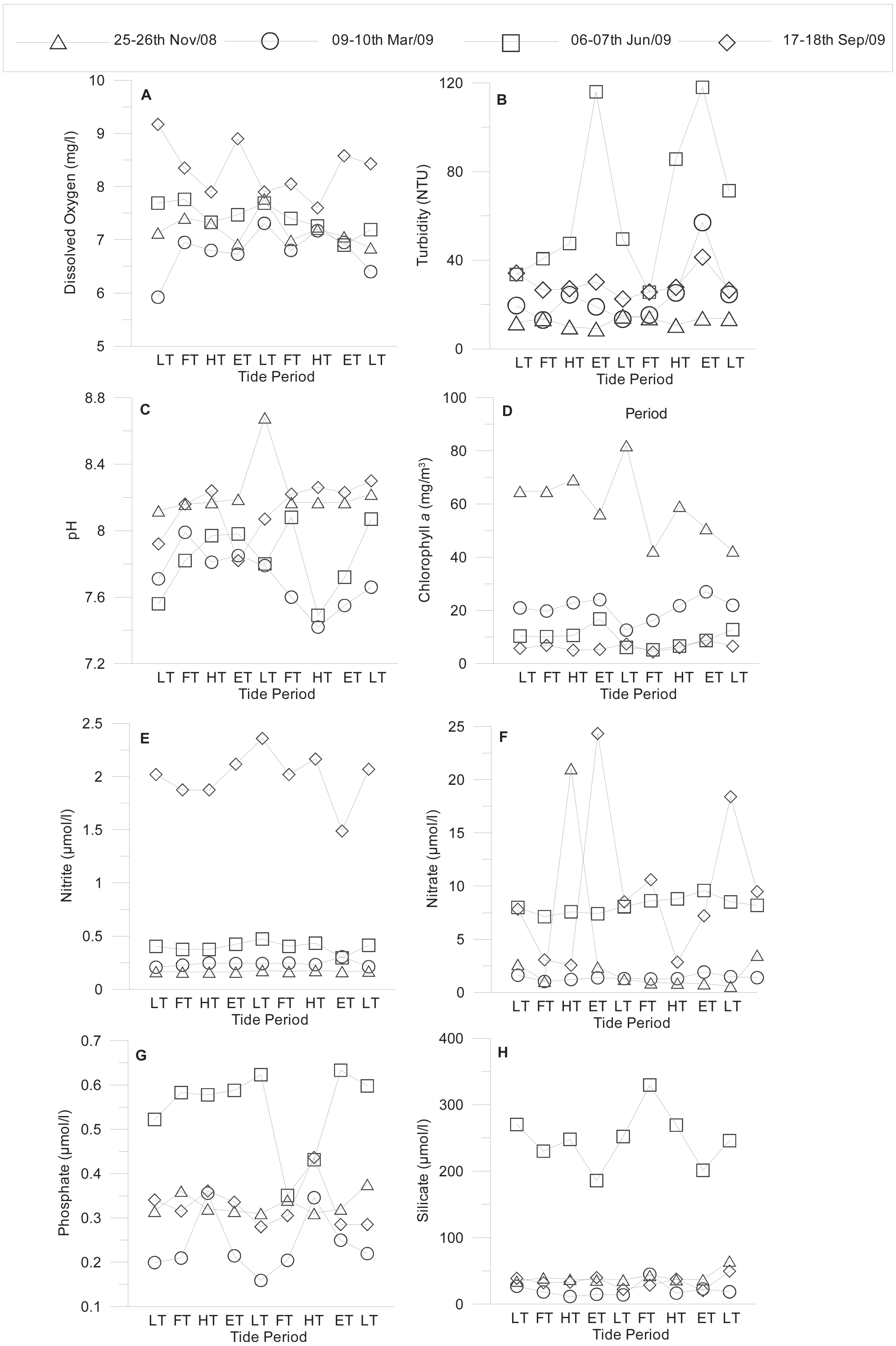

Figure 7. Hydrologic measurements taken at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

seasonal fluctuations in hydrologic variables. Salinity and pH were significantly lower in the rainy season, as a result of both high precipitation rates—especially in March—and increased fluvial discharge, culminating in June. Fluvial discharge data are not available for the smaller rivers in the Amazon region, but studies undertaken by Curtin and Legeckis (1986) showed that the peak discharge of the Amazon River occurs in May–June (2.3×10^5 m^3/s), and the minimum discharge between

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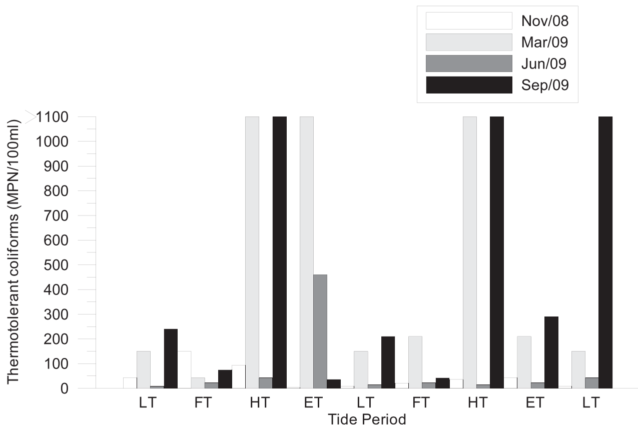

Figure 8. Thermotolerant coliform data (MPN/100 ml) at Atalaia beach during the studied period. FT, flood tide; HT, high tide; ET, ebb tide; LT, low tide.

October and December (0.9×10^5 m^3/s). River discharge in the region is therefore three times larger in May–June than in October–December, which is coincident with the lowest and highest water salinity and pH in the study area. Similar patterns have been recorded at other sites along the Amazon Coast, with salinity varying from <10 psu in May and June to >35 psu in October–December, and pH varying from slightly acid to alkaline between the same periods (Costa, Leite, and Pereira, 2009; Guimarães *et al.,* 2009; Leite, Pereira, and Costa, 2009; Pereira *et al.,* 2009; Silva *et al.,* 2009).

High oxygen concentrations (>5 mg/L) appear to be typical of the waters of the Amazon coastal zone (Costa, Leite, and Pereira, 2009; Pereira *et al.,* 2010; Silva *et al.,* 2009), but while some studies (Guimarães *et al.,* 2009; Santos *et al.,* 2008) have related an increase in dissolved oxygen to phytoplankton growth, the main determinant in the present study appeared to be the intensity of the water–atmosphere interaction. In September, when the highest oxygen concentrations were recorded, the hydrodynamic regime was characterized by strong winds and high (equinoctial) tides. An additional factor may have been the fact that the samples were collected in a zone of high turbulence, *i.e.,* the surf zone (Silva *et al.,* 2009; Sousa *et al.,* 2009).

The highest turbidity was also recorded in the rainy season month of June, when fluvial discharge was at its greatest, but it was also relatively high in the equinoctial months of March and September, when the high tides generated strong hydrodynamic conditions. In terms of suspended sediment, the waters flowing onto the Amazon continental shelf are highly turbid due to the high sediment load of the Amazon River (which has one of the highest discharge rates in the world). In addition, the Amazon macrotidal mangrove coast is traversed by 23 estuaries, which provide a plentiful supply of fluvial sediments (Silva, Souza-Filho, and Rodrigues, 2009). However, Atalaia is situated east of the Amazon River and adjacent to estuaries of relatively modest size, with reduced water discharge and turbidity in comparison with other beaches in the region (Monteiro, Pereira, and Oliveira, 2009; Silva *et al.,* 2009).

On the Amazon Coast, chlorophyll *a* concentrations are generally considered to be an index of the density of microalgae. In the present study, the highest concentrations were recorded in November (second highest was in March), when the water was less turbid, and sunlight penetration was at its maximum. An additional factor may have been the great wave heights (*Hs*) and relatively strong tidal currents recorded during those periods, which may have contributed to the increase in chlorophyll *a* due to the resuspension of phytobenthic species into the pelagic environment (Pereira *et al.,* 2010; Sousa *et al.,* 2008, 2009).

The vast and complex estuary system found on the Amazon Coast is an important source of nutrients for the continental shelf (Edmond *et al.*, 1981). DeMaster and Pope (1996) recorded high concentrations of dissolved nutrients on the Amazon continental shelf resulting from both the input from the mangrove system and the resuspension of fine-grained and organic sediments by the strong tidal currents. In the present study, the water was eutrophic, and the highest dissolved nutrient concentrations were recorded in September (nitrite and nitrate) and June (phosphate and silicate). In September, this pattern was likely due to the high equinoctial tides reaching the most elevated parts of the mangrove (mangrove supply), and the high hydrodynamic energy (strong currents and waves), which favored the resuspension of nutrients from the bottom. In addition, we also observed an increase of sewage discharge onto the beach in September (equinoctial spring tide—dry season) in comparison with March (equinoctial spring tide—rainy season) as a result of a slight increase of beachgoers during the dry season. In June, the primary factor was the high fluvial discharge. Whereas Edmond *et al.* (1981) and DeMaster, Kuehl, and Nittrouer (1986) recorded algal blooms on the Amazon shelf during periods of high nutrient concentrations, in the present study, the highest chlorophyll *a* concentrations were recorded in the months with the lowest nutrient concentrations (November and March), but in substantial amount. It seems possible in those months, at least, the algal bloom were related to low turbidity.

Overall, the results of this study indicate that physical processes are the main factors responsible for the high turbidity, high chlorophyll *a*, high dissolved oxygen and nutrient concentrations, and low salinity (rainiest months) of the water in the study area. While the high turbidity and algal blooms appear to be a natural phenomenon, the beach would be considered inappropriate for recreational use, based on the criteria of CONAMA (2005) and the Blue Flag Program (2007). These water criteria demand, for example, virtually no turbidity or abnormal changes in the water color. The turbidity in the study area—and other beaches of the region—is a result of high fluvial discharge and hydrodynamic energy, whereas the phytoplankton blooms in the study area were a combination of the dissolved nutrients supply and a period of higher light penetration. Thus, it seems clear that the values used by these authorities are inappropriate for the unique natural conditions prevailing on the Amazon Coast and that the criteria should be carefully reassessed and redefined for application in this region, which presents estuarine characteristics during the rainy season and marine characteristic during the dry season.

Figure 9. Study area during low tourist season ([A] restaurant buildings and [B] restaurants' facilities on the beach), the presence of cesspits and sewage (C–D) and high tourist season (E–F).

Human influence

Bacteriologic contamination indicates the effects of anthropogenic pressures on Atalaia beach. The results of this study have shown that the beach's water, which is used intensively for recreational purposes (bathing, water sports), has been affected by bacterial contamination (thermotolerant coliforms) during low peak season (Figures 9A–B), as a result of unregulated occupation of the coastline and the lack of a public sanitation system. The presence of cesspits in the intertidal zone and the discharge of domestic sewage directly onto the beach (Figure 9C–D) are the primary factors determining the bacteriologic quality of the water. The high thermotolerant coliform concentrations (>1100 MPN/100 ml) observed during the equinoctial spring tide events (March and September) indicate that the exceptionally high tides typical of this period reached the level of the cesspits in the intertidal zone. This is also the time of year when local residents empty their cesspits, which further contributes to the contamination of the beach's water, which has become inappropriate for recreational use, according to CONAMA and Blue Flag criteria.

Contamination levels may have been underestimated here, given that the peak vacation period (July) was not sampled (Figures 9E–F), and the area's high hydrodynamic energy implies a rapid turnover and renovation of the water. The high dissolved nutrient concentrations recorded in September may also have been related to the lack of a public sanitation and drainage system associated with a slight increase of beachgoers. Previous studies have shown that the discharge of sewage in urban areas of the Amazon Coast has been contributing to increasing contamination of both estuarine and coastal marine waters (Guimarães *et al.,* 2009, Silva *et al.,* 2009).

FINAL CONSIDERATIONS

The characteristics of the water used for recreation in the study area were influenced by seasonal climatic patterns, hydrodynamic conditions, and human activities. Fluvial discharge and equinoctial spring tides were the main factors controlling the seasonal oscillations of hydrologic variables. Bacteriologic contamination resulting from the sewage discharged directly onto the beach proved to be the main factor affecting local water quality.

This work showed that environmental characteristics of the Amazon beaches are completely different from other Brazilian beaches. So, specific evaluation criteria on environmental aspects must be elaborated for this region. Further studies in other Amazon beaches are also necessary to determine appropriate index values of hydrologic variables regarding the choice of proper standards of water quality.

A number of measures would help to improve the quality of the water at Atalaia beach, including: (i) regulation of sewage disposal by both commercial and residential premises; (ii) removal of cesspits from the intertidal zone and dune system in order to eliminate contact with groundwater and adjacent marine coastal waters; (iii) immediate implementation of a public sanitation system or at least a regular cesspit drainage protocol; (iv) continuous monitoring of the physical, ecologic, and social elements of the coastal zone in order to guarantee adequate delimitation of proper and improper bathing areas, mainly during the peak tourism season; and (v) regulation of land use to reduce pressures on the coastal environment.

These measures should improve prospects for the development of the local tourism industry and thus contribute to the expansion of the local economy without affecting the environment adversely. Coastal management guidelines, which could include specific legislation, policies, and supporting infrastructure for sustainable development, appear to be vital to the future of this sector of the Amazon Coast.

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□ RESUMO □

A praia de Atalaia está situada no nordeste do estado do Pará (Brasil), e é uma das mais turísticas e populares praias do litoral amazônico. O objetivo deste trabalho foi descrever as variações sazonais das condições meteorológicas e oceanográficas da área estudada, bem como conhecer os efeitos da falta de um sistema público de saneamento básico sobre a qualidade da água utilizada para banho pelos usuários desta praia. Campanhas oceanográficas foram realizadas entre novembro de 2008 e setembro de 2009 e dados meteorológicos foram fornecidos pelo Instituto Nacional de Meteorologia. Os resultados mostraram que a área de estudo é caracterizada por possuir altas precipitações (>1900 mm durante o período chuvoso), ventos de nordeste com velocidades médias de até 4,36 m/s no período seco e 3,06 m/s no período chuvoso, macromarés com alturas acima de 4,0 m, correntes de marés com velocidades médias de até 0.5 m/s, e altura de ondas significantes de até 1,5 m. A temperatura da água foi relativamente homogênea (27,6 a 29,3°C). A salinidade variou de 5,7 (junho) a 37,4 psu (novembro). A água foi bem oxigenada (até 9,17 mg/L), turva (até 118 NTU), alcalina (até 8.68), eutrófica (máximo de 2,36 μmol/L para nitrito, 24,34 μmol/L para nitrato, 0,6 μmol/L para fosfato e 329,7 μmol/L para silicato), e apresentou altas concentrações de clorofila *a* (até 82 mg/m³). As condições naturais observadas no presente estudo indicam a necessidade da revisão dos critérios de qualidade da água das praias amazônicas, estabelecidos por agencias nacionais e internacionais. Por outro lado, a falta de um sistema público de saneamento tem causado contaminação bacteriológica e comprometido a qualidade da água da praia de Atalaia.

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