ABES

Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Socially-driven risk in a town of the Amazon coastal zone: the case of Vigia de Nazaré, in Pará state, Brazil

O risco socialmente construído em uma cidade da zona costeira amazônica, dinâmica ambiental e ocupação do solo em Vigia de Nazaré/PA, Brasil

Cairo Eduardo Carvalho Barreto[1], *Marcia Aparecida da Silva Pimentel*[1]

ABSTRACT

Vigia de Nazaré is a town located in the northeastern extreme of the Brazilian state of Pará, in the Pará Coastal Zone, a sub-region of the Amazon Coastal Zone. The town sits on the lower levels of the region's terraces, and on fluviomarine plains. The different stages of its sociospatial evolution reflect the problem analyzed here, in particular, the occupation and urban development of the fluvial-marine plains, which was occupied spontaneously by large numbers of families, most of which are socially vulnerable. The present study investigated the physical and social processes that led this urban space's vulnerability to hydrometeorological hazards, based on an integrated historical-geographic approach and the inherent precariousness of the environment. The data analysis revealed high levels of annual precipitation in the region, with a well-defined rainy season between January and May (mean monthly precipitation of over 300 mm), in an environment dominated by semidiurnal macro tides with amplitudes of up to 4.5 meters. In 2022, the high tide reached at least 4.2 meters in 60 occasions — the level of alert for possible rainfall-induced tidal surges. The recent occupation of the urban zone is concentrated on the low-lying areas of the fluviomarine plain, which recently account for one-third of the urban center. These areas are exposed to the hydrological dynamics of the local estuarine environment, which result in environmental degradation and hydro-morphodynamic processes alteration.

Keywords: hydrometeorological hazards; floodplain; tide; flooding; risk management.

RESUMO

A cidade de Vigia de Nazaré, nordeste paraense, está situada em uma sub-região da Zona Costeira Amazônica, a Zona Costeira Paraense (ZCP), assentada nos níveis mais baixos dos terraços regionais e em planícies fluviomarinhas. Etapas da formação socioespacial da cidade evidenciam a problemática aqui analisada: a anexação de planícies fluviomarinhas ao contexto urbano, servindo para o assentamento espontâneo de diversas famílias, em sua maioria em situação de vulnerabilidade social. O objetivo é compreender, sob a perspectiva histórico-geográfica e da vulnerabilidade inerente, uma análise integrada dos processos físicos e sociais que expuseram e criaram no ambiente urbano espaços de vulnerabilidade ao risco hidrometeorológico. A análise dos dados revelou altos acumulados de precipitação anual para o contexto regional, com um período chuvoso bem definido, que duram de janeiro a maio (acima de 300 mm em média), posto em um ambiente sob influência de macromarés semidiurnas, podendo alcançar 4,5 m. Para o ano de 2022, foram verificados 60 registros de maré iguais ou acima de 4,2 m, nível de alerta local para coincidência com chuva. A ocupação recente deu-se em sua maior parte no nível morfológico de menor altimetria, a planície fluviomarinha urbanizada alcançou 1/3 do núcleo urbano. Este local, exposto à dinâmica do ambiente costeiro estuarino, exprime atualmente aspectos da degradação ambiental e alteração dos processos hidromorfodinâmicos.

Palavras-chave: risco hidrometeorológico; planície de inundação; maré; inundação; construção do risco.

[1]Universidade Federal do Pará – Belém (PA), Brazil.

Correspondence address: Cairo Barreto – Centro Gestor e Operacional do Sistema de Proteção da Amazônia – Av. Júlio César, 7060 – Val de Cans – CEP: 66617-420 – Belém (PA), Brazil.

E-mail: cairobarretoufpa@gmail.com

Conflicts of interest: the authors declare that there are no conflicts of interest.

Funding: Brazilian Coordination for Higher Education Personnel Training (CAPES).

Received on: 01/27/2023. Accepted on: 06/15/2023

https://doi.org/10.5327/Z2176-94781546

Introduction

Coastal zones are mosaic landscapes formed by the morphogenesis of the contact between marine and terrestrial environments. These zones are dynamic, integrated ecosystems, molded by a systemic combination of terrestrial, oceanic, and atmospheric processes that evolve across distinct temporal and spatial scales (França and Souza Filho, 2003; Oliveira, 2010; Souza, 2013; Fernandez and Rocha, 2022). The environments of the Pará Coastal Zone (PCZ) encompass a diversity of hydrogeological processes with an intrinsic dynamic that supports a high level of environmental instability through morphogenesis, given that they are open, non-isolated systems in which human activities reinforce positive retroactions, intensifying degradative processes (Tricart, 1977; Fernandez and Rocha, 2022).

The science of socioenvironmental risk is multidisciplinary, and is based on three principal concepts (with some variation): risk, susceptibility, and vulnerability. Risk refers to the probability of an event, which reflects its unpredictability, the product of susceptibility and vulnerability. Susceptibility, or threat, is a specific characteristic of the environment, related to a certain phenomenon. Vulnerability is the condition of specific groups of society in the face of the environment characteristics and the threats it poses (Girão et al., 2018). It is important to note here that this threat arises when a population is exposed to a specific natural phenomenon that has been modified to create a socially-driven hazard, which is often institutionalized.

In recent years, the science of risk has advanced in terms of research and institutional management, due to the integration of different scientific disciplines, together with an increase in disaster frequency. A total of 38,996 disasters were recorded officially by the Brazilian federal government between 1991 and 2012, although the total number recorded between 2010 and 2012 was similar to the whole 1990s, peaking in 2020 with 3,970 events, and in 2021, with 3,660 occurrences (Brasil, 2022). These events had obviously a significant impact on the government's budget and financial constraints (Nina and Szlafsztein, 2018). The increasing investment in research in the science of risk began to alter the institutional scenario, which had previously appeared to involve only a concern with the aftermath of disasters. In this modern scenario, coastal ecosystems, in particular, provide a bellwether of this shift, given the susceptibility of these environments, mainly in the context of rising sea levels and the increasing intensity of extreme climatic events (Braga et al., 2020; IPCC, 2021).

As a major continental-estuarine interface, the PCZ encompasses a number of critical areas in terms of hydrometeorological hazard risks. The low-lying coastal morphological units and the topographic variation within a region of considerable tidal amplitude combine to form a scenario prone to floods that may reach hundreds of kilometers inland (Barbosa, 2007). In this context, even the occupation and alteration of the Amazon coastal plains with adequate infrastructure, it is impossible to avoid the cycle of flooding in many areas, caused by the combination of high tides and pluvial runoff (Luz et al., 2015).

Vigia de Nazaré, a town located in the continental-estuarine region of the PCZ, is set within a transitional zone of continental and coastal features. Much of its urban infrastructure is located in low-lying areas, covering approximately 0.95 km² in 2014, which corresponds to around 22.17% of the urban zone, i.e., 4.28 km² (Barbosa and Bentes, 2016; IBGE, 2021). Santos (2009) reported that the urban expansion of Vigia has destroyed the town's ecological heritage. This recent expansion occurred primarily on the fluviomarine plain, which is affected by intense fluvial, marine, and continental processes.

These spaces express the vulnerability of the population that occupies them. In their review of vulnerability concepts, Canil et al. (2020) refer to a key point when analyzing the "inherent vulnerability" of certain socioeconomic development models, in which risks and disasters are processes constructed socially and politically. The absence of the state is a significant factor in these cases since these environmental risks are products of the public administration negligence at all levels, ranging from the need to combat poverty, basic education, environmental conscientization, and the regulation of land use and occupation, at both regional and local perspective. In particular, the development of urban centers and the expansion of infrastructure tend to follow the logic of the real estate market, creating a predictable pattern in Brazilian towns and cities (Trindade Jr., 2018).

In the specific case of Vigia, the occupation of the low-lying fluviomarine plain combined with the installation of relatively precarious infrastructure and the intense hydrometeorological dynamics of this region of the Amazon coastal zone all contribute to the risks of environmental disaster. The present study investigated this scenario from a historical-geographic perspective and the concept of inherent vulnerability, combined in an integrated analysis of the physical and social drivers that expose these urban spaces to hydrometeorological hazard risks.

Methods

The first step in the development of the present study was a literature search on the environmental dynamics and regional and local processes of occupation, from a historical-geographic perspective, followed by the cartographic analysis and geoprocessing of the hydrometeorological variables, statistical analysis of precipitation and tidal data, and fieldwork. The analysis of the urban area of Vigia de Nazaré was based on the publications available in the town and its surroundings. Although not extensive, there is a solid database on the socio-environmental features of the study region, such as the studies by Palheta (1980), Barbosa (2007), Santos (2009), Barbosa and Bentes (2016), and Bentes (2020).

The tidal data used in the present study are estimates for 2022 produced by SisBaHiA: Environmental Hydrodynamics Base System (*Sistema Base de Hidrodinâmica Ambiental*). This freeware applies a harmonic analysis based on observation of the target area, which reproduces the tidal amplitudes and the phases of its components, which are known as "constants". Once these constants are specified, it is possible to predict the tide level at a given point over a specific time interval. The tidal data used here were obtained from the National Oceanographic Database (BNDO: *Banco Nacional de Dados Oceanográficos*) of the Brazilian Navy for Hydrography Center (CHM). The data were obtained for a one-month period, the minimum recommended by the SisBaHiA, between May 12th and June 12th, 2002, using a buoy and counterweight at hourly intervals, and measured in centimeters (CHM, 2002).

The precipitation data were obtained from the HidroWeb platform, a tool provided by the Brazilian National System for Data on Water Resources that gives access to data from the National Hydrometeorological Network. Specifically, the data were from rain gauge 48006 (Latitude: -0.87°, Longitude: -48.11°), which is maintained by the National Water and Sanitation Agency (ANA) and operated by the Brazilian Geological Survey (SGB/CPRM). The historical series includes data from January 1st, 1982 through May 31st, 2021. The rain gauge is installed approximately 2.1 km east of the study area polygon. These data were corrected and compiled following Tucci (2012) and Collischonn and Dornelles (2013).

The data were used to establish monthly, seasonal, and annual variations in local precipitation patterns, based on graphic plots. The first plot is the Standardized Precipitation Index (SPI) by McKee et al. (1993), which creates a probability density function to describe the time series (Santos et al., 2017). The analysis of the accumulated annual precipitation provides insights into annual variability, and the potential influence of regional and global oceanic-atmospheric systems on local precipitation patterns. This approach is based on a boxplot of the data, which divides the series into three quartiles, with four partitions of 25%, based on the overall data for each month. In addition to the quartiles, this analysis provides the minimum, maximum, mean, and median values, i.e., P15, P35, P65, and P85 (Collischonn and Dornelles, 2013; Pinkayan, 1966; Tucci, 2012). These analyses were run in Excel® 365 MSO, version 2207 and RStudio ©, version 2022.02.0.

Cartography and geoprocessing also provided relevant insights for the development of the scenarios proposed here, based on three maps of the study area. The map of the local environment elements was based on a false-color Landsat 8 satellite image. The other maps were based on a high-resolution color orthomosaic and polygons that delimited the floodplain and were extracted from the Digital Terrain Model (DTM). This material was provided by the Belém Regional Managerial and Operational Center of the Amazonian Protection System (CENSIPAM-CRBe). These products were requested from the CENSIPAM through the Integrated Hydrometeorological Monitoring and Early Warning System (SIPAMHidro), a project that maps areas subject to flooding. The images were prepared between December 27th and 29th, 2021, in the presence of the first author.

The fieldwork involved the collection of photographic images, descriptions of the local environment, and occupation areas, and finally, the application of interviews with selected residents to obtain information on the flood cycle in the town. This fieldwork was conducted on the 27th and 28th of December 2021. The collection points were defined based on Barbosa and Bentes (2016) floodplaind delimitation. The interview was based on two questions:

1. *Does this street flood? ( ) yes ( ) no.*
2. *If yes, what types of damage or loss have occurred here? (Material or personal).*

The final step was to determine the altimetric definition of the fluviomarine plain and the lowland terraces (see Table 1).

To analyze the social construct of risk from a historical-geographic perspective, the present study identified the physical factors of the hydrometeorological threat that compose this unstable and dynamic environment, and established the chronology of the historical occupation of the fluviomarine plain, in order to determine its sociospatial contradictions. The studies of Rodrigues (2015) and Canil et al. (2020) were essential for the establishment of the inherent vulnerability approach for the assessment of the population that occupies these areas of risk, as a complement to the historical-geographic perspective.

Table 1 – Material used to delimit the extent of the floodplain within the study area.

Type of material	Source	Product
Literature search and cartographic material	**Barbosa (2007); Barbosa and Bentes (2016); Luz et al. (2015) and Palheta (1980)**	**Published data and environmental maps**
Photographs and interviews with local residents on the occurrence of flooding, with geolocated points.	Fieldwork	Geolocation of flooding points
Flooding points identified from social media and the press	Barreto (2022)	Geolocation of flooding points
Historical images of the Spot 1 (1988) and Spot 5 (2002), and Sentinel 2A (2019) satellites	Barreto (2022)	Occupation of the land
Digital Terrain Model (DTM) and Contours	CENSIPAM	Altimetric definition of the floodplain
Orthomosaic of the urban area of Vigia	CENSIPAM	Color orthophotograph mosaic of Vigia's urban area

Literature search

The synchronization of policies and practices for the Reduction of Risks and Disasters (RRD) will be essential for the long-term security of Brazilian coastal towns and cities. For a national RRD plan to be effective, it will be necessary to guarantee the balance of adaptive mechanisms (Ishiwatari and Surjan, 2019). In particular, studies of the risks of urbanization and environmental alterations of coastal towns, still largely ignored, will be essential for the adequate planning of strategies in the coastal environment (Marengo et al., 2022). Recent studies of the economic impacts of flooding (Cruz Primo and Rafaeli Neto, 2023), oil spills (Mussi et al., 2022), and the installation of wind farms (Clemente de Lacerda et al., 2022) on the Brazilian coast are all examples of this research on the impacts of anthropogenic change.

The municipalities located within most of the coastal zone of Pará, which are typically estuarine environments, generally have a relatively narrow coastal plain, with much less extensive mangroves than the eastern extreme of this littoral, and the neighboring areas of the state of Maranhão. The mangroves become even less extensive moving upriver into the Rio Pará estuary, where they begin to intergrade with freshwater swamps and marshes (*igapó* and *várzea*) as the salinity of the water decreases (Barbosa, 2007; Hayashi et al., 2019).

The urban zone of Vigia encompasses two morphological features, the fluviomarine plain, and, further inland, lowland terraces, which are modeled primarily by the accumulation of sediments, through a diversity of morphogenetic processes and the genesis of the coastal environments. The coastal plain is the product of processes of fluvial and marine accumulation, which may include fluvial channels subject to periodic flooding, common in estuaries and low-lying coastal areas. The terraces of the fluviomarine environments, by contrast, are formed by an accumulative process further inland, on flat or slightly sloping terrain, which has been molded by fluctuations in sea level, and associated erosive or, in some cases, neotectonic processes. These processes are common on Pleistocene and Holocene coastal lowlands (Palheta, 1980; IBGE, 2009).

Vigia de Nazaré faces the mouth of a channel known as the Furo da Laura (Figure 1). In the Amazon region, a "furo" is a drainage channel that links two bodies of water, such as rivers and lakes, or sub-estuaries, that is, tidal channels (Gomes et al., 2020). In this case, the Guajará-Mirim River functions as a sub-estuary that discharges into the Gulf of Marajó, defined as a tidal fluvial zone (Kjerfve, 1990). The margins of Furo da Laura are dominated by deposits of estuarine sediments, with Holocene marshes and mangroves, associated with the geoevolution of the Neogene and Holocene (Lima et al., 2015).

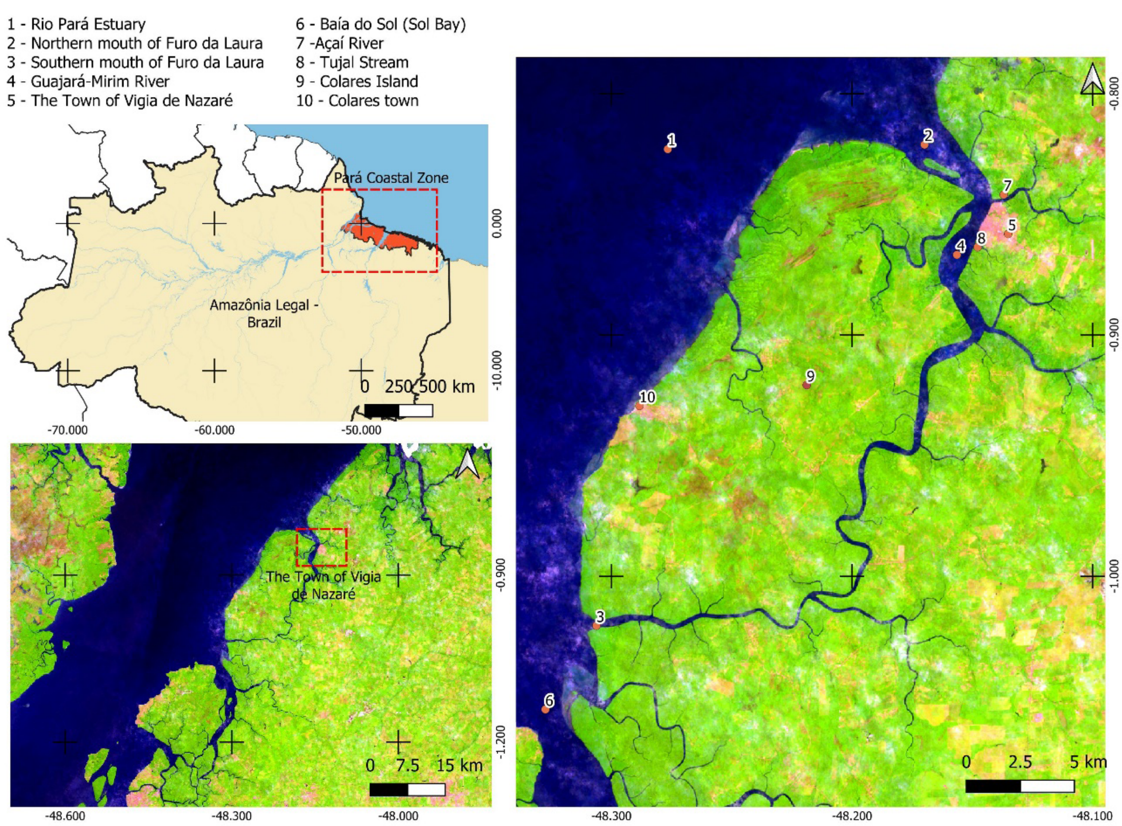

Figure 1 – Location of the study area, showing the principal hydrological and terrestrial features of the local landscape.
Source: Barreto (2022).

The local environment is dominated by macro tides, which originate tidal currents that, combined with fluvial discharge, regulate the local hydrological patterns. These tides have an amplitude of approximately 4.5 meters and are typically semidiurnal, with two complete cycles per day (Lopes, 2016).

The spatiotemporal variability in the precipitation levels of the Brazilian Amazon has been widely studied, and the data indicate that the highest rainfall occurs in the northwestern extreme of the basin (Villar et al., 2009). In the state of Pará, the precipitation intensifies during the austral summer and fall, related primarily to large-scale, quasi-stationary atmospheric circulation patterns, such as the South Atlantic Convergence Zone (SACZ) and the Intertropical Convergence Zone (ITCZ) (Ferreira et al., 2015). Instability lines also form along the Atlantic coast of northern and northeastern Brazil, due to trade winds. These coastal instability lines are most active between April and August (Cohen et al., 1995). Other events at a global scale, including the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and El Niño Southern Oscillation (ENSO), also contribute to the formation of this general climatic scenario (Amanajás and Braga, 2012).

Political and economic processes have also left their mark on the Amazon region, and the process that most impacted its urban spaces was the regional restructuring, initiated in the 1960s. This was a strategic integration policy between the Amazon region and the rest of Brazil, and the world, implemented by the Brazilian government (Becker, 2001). The previous configuration, based on rivers as routes of communication and riverside lifestyle, was not replaced, but rather incorporated into the new reality. This coexistence of different times and spaces produces an urban diversity quite distinct from the perspective of a homogeneous region (Trindade Jr., 2022).

Results and Discussion

Analysis of the tides

Lopes (2016) describes the tides of the study region as macro tides (IBGE, 2011), whose amplitude may reach 4.56 meters. A total of 36 harmonic components were identified in the analysis, of which, the most important were components M2 (principal semidiurnal lunar component), S2 (principal semidiurnal solar component), and N2 (elliptical lunar component), which were used as parameters for the prediction of the tides of 2022.

The tides are clearly semidiurnal, F = 0.129 (Dietrich, 1963), with a mean amplitude of 2.29 m, with the highest tide (4.52 meters) being predicted for January (Table 2).

During the rainy season, the prediction indicated three highest tides, invariably above 4.31 meters, in particular, in December, January, and February. January, March, and April were the rainy season months with the highest mean high tides. July, a dry season month, had the highest tide recorded during this season, but not the highest mean tide. The moon phases also had a clear influence in February, March, and April (Figure 2), when the spring tides were associated with the greatest amplitudes, and the neap tides, with the smallest amplitudes. The equinoctial spring tides peaked in March, which is also the peak of the rainy season, while the mean high tides recorded in September were the highest of the dry season.

In March and April 2020, the municipal authorities of Vigia published a warning on their official site (Prefeitura de Vigia de Nazaré, 2020), alerting to the "High risk of the combination of high tides with intense rainfall", with alerts of 4.2–4.3 meters high tides. Semidiurnal tides of over 4.2 meters were predicted on 60 occasions in 2022. However, floods were recorded on days when the tidal amplitude was well below the maximum level. Given that Vigia has one of the region's highest mean precipitation rates, as discussed below, the configuration and prediction of the tides should be a constant concern, mostly on the part of municipal authorities.

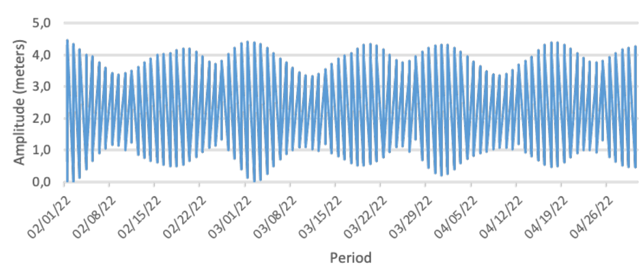

Figure 2 – Tide chart for February, March, and April 2022.
Source: Barreto (2022).

Table 2 – Tides predicted for 2022 in Vigia de Nazaré.

Parameter	Value (m)											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Maximum	4.52	4.46	4.42	4.40	4.40	4.46	4.50	4.47	4.41	4.37	4.37	4.43
Next highest	4.51	4.37	4.38	4.39	4.40	4.42	4.47	4.47	4.40	4.34	4.36	4.43
Third highest	4.49	4.33	4.35	4.32	4.35	4.41	4.42	4.39	4.38	4.33	4.32	4.34
Minimum	0.09	-0.02	0.01	0.25	0.42	0.31	0.09	-0.03	0.04	0.23	0.37	0.29
Mean	2.34	2.33	2.34	2.34	2.34	2.33	2.33	2.33	2.34	2.33	2.34	2.34
Mean high tide	3.88	3.84	3.88	3.86	3.85	3.83	3.83	3.84	3.85	3.85	3.85	3.84

Analysis of rainfall patterns and the regional precipitation systems and mechanisms

The boxplot (Figure 3) of the mean precipitation rates recorded in Vigia reveals monthly and seasonal patterns typical of the study region. This is consistent with the findings of previous studies based on different methods (Amanajás and Braga, 2012; Ferreira et al., 2015; Santos et al., 2019).

In Vigia, the rainiest months of the year are from December through May, a pattern determined by the influence of the ITCZ on global precipitation systems. Historically, the rains peak in February, March, and April, with March being the rainiest month, followed by April. The rains continue through July, with monthly means of approximately 200 mm, which reflects the persistence of the instability lines, and that remain in place until August (Cohen et al., 1995). Rainfall in August usually begins below 200 mm, lasting through the driest months of September, October, and November, as recorded by Andrade et al. (2017) for the Salgado micro-region.

The proximity of the mean and median values indicates that extreme values did not affect the historical means, particularly in the rainy season. The length of the boxes in the boxplot for the rainy season months indicates the difference between the highest and lowest values, which are highly representative. In March, for example, 50% of the values between Q1 and Q3 ranged from just over 400 mm to almost 550 mm, reflecting the consistently high precipitation rates recorded in this month. Outliers appeared only in the driest months, as a consequence of the much lower values, which made any deviation seem much more isolated from the mean values.

The pattern observed in this plot (Figure 4) is consistent with the known variation in the Sea Surface Temperature (SST) associated with ENSO events, and the phenomena described by the American National Oceanic and Atmospheric Administration (NOAA) and the Weather Forecasting and Climatic Studies Center (CPTEC/INPE) of the Brazilian National Institute for Space Research. In the case of the warm, El Niño phase, which provokes a decrease in the rains in the Amazon region, droughts were recorded in 1991–1992 (moderate), 1997–1998 (light), 2005 (severe), 2010 (light), and 2015–2016 (moderate). La Niña, the coolest phase, which provokes an increase in precipitation rates, presented extremely high levels in 1999–2000 and 2020–2021, and a moderate increase in 2017–2018 (CPTEC, 2022; NOAA, 2022).

These findings, such as the deficit in rains in 2005 (one of the most severe droughts recorded in the Amazon region) and 2010, are contradicted by the results of some studies, which indicated a strong link with the tropical Atlantic Ocean temperature. The 2010 drought was influenced by successive El Niño (ENSO) events combined with high temperatures in the tropical North Atlantic (Espinoza et al., 2019). Villar et al. (2009) verified an opposite pattern in 1995, when La Niña provoked positive variation in inter-annual precipitation patterns.

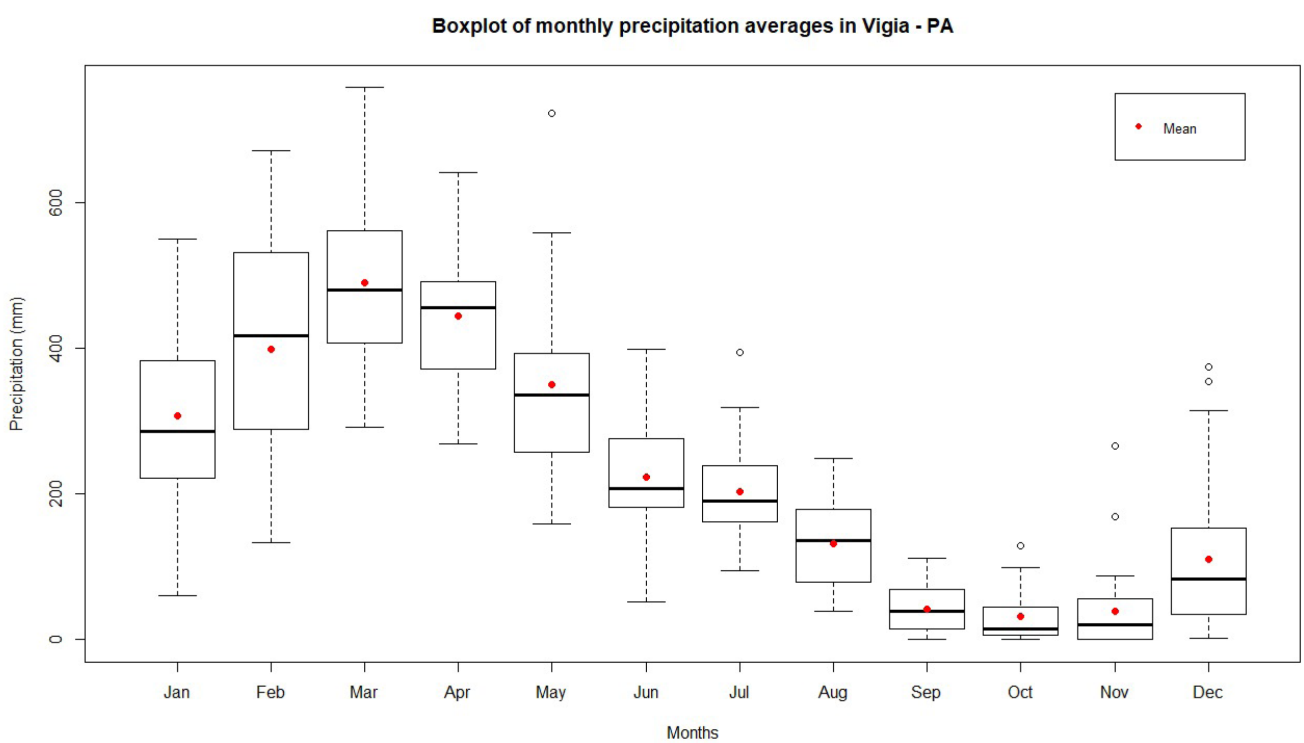

Figure 3 – Boxplot of the mean monthly precipitation recorded in Vigia de Nazaré, Pará, northern Brazil, between 1991 and 2020.
Source: Barreto (2022).

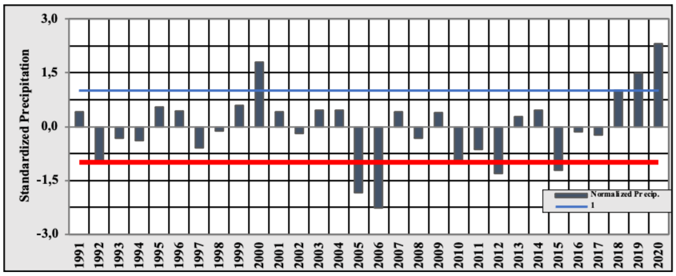

Figure 4 – Standardized annual precipitation rates at Vigia de Nazaré, Pará (Brazil) for the historical series (1991–2020).
Source: Barreto (2022).

Table 3 – Population resident in the rural and urban zones of the municipality of Vigia de Nazaré, Pará (Brazil), according to the national censuses between 1970 and 2010.

Type of residence	Number of inhabitants in:				
	1970	1980	1990	2000	2010
Total	19,261	24,825	37,418	40,176	47,889
Urban	11,681	16,684	25,166	28,006	32,353
Rural	7,580	8,141	12,252	12,170	15,536

Source: IBGE (2021).

History of Vigia de Nazaré: phases and characteristics of the formation of the urban center

Population drivers

In 1885, 70% of Vigia's population lived in the rural zone, a pattern that has reversed in recent years. In 1970, 60.6% of the municipality's population inhabited urban areas. This percentage increased to 67.5%, according to the 2010 Census (Table 3). Currently, 31,000 of the 32,300 urban residents of the municipality live in the town of Vigia, while the other 1,300 are residents in the settlement of Vila de Porto Salvo (IBGE, 2021).

Vigia's population grew by over 12,000 inhabitants between 1980 and 1990, reaching 37,418 people in the municipality as a whole at the end of the decade, the largest increase ever recorded by the Brazilian Census (IBGE). This growth coincided with the increasingly intense occupation of the town's low-lying areas (Bentes, 2020), which are exposed to regular flooding.

Bentes (2020) identified four principal phases in the urban environment evolution of Vigia:

- 1616–1854, initial development of the site outpost, settlement, and village;
- 1854–1960, formation of a coastal riverside town;
- 1960–2000, development of a hybrid town, that integrated the river with the newly-constructed highway, resulting in a high level of urban diversity;
- 2000 onward, the current phase of interiorization.

The first and second phases were dominated by the coast occupation, with two nuclei, Vigia and Arapiranga. It then evolved into a process of interiorization in the third phase, with the occupation migrating toward the PA-412 state highway and in the area surrounding the original nucleus of the town, through the establishment of new neighborhoods. The occupation and modification of the floodplains of the local sub-basins began in the second phase and peaked during the third phase, concentrating invariably on the area around the center, which is located on the highest terrain.

The spontaneous occupation of low-lying areas in urban centers in the Amazon region is similar to the unregulated occupation of marginal urban habitats – often on steep hillsides – of other Brazilian regions. Nevertheless, Vigia has some unique features, in particular, in terms of the dynamic nature of recent occupation patterns. The areas are located on flat land adjacent to bodies of water, mostly at elevations below 4.5 meters, where the backyards of the residences are typically filled with discarded building material and açaí seeds. The local population is mostly poor, black, and migrated to the town from the local islands or the interior of Pará. These settlements occupy spaces that were historically overlooked by local real estate developers, despite their relatively central location and accessibility (IPEA, 2016; Miranda, 2020).

Relationship between environmental and social drivers

Barbosa and Bentes (2016) divided the lowland tracts of the study area into three sectors (Figure 5), based on the hydrographic sub-basins arrangement within the town area and the neighborhoods that occupy these sub-basins:

- Sector I – Igarapé Tujal (*Tujal Stream*), the southern part of the town, including four neighborhoods: Centro, Pantanal, Castanheira, and Vila Nova;
- Sector II – Igarapé da Rocinha (*Rocinha Stream*), in the central part of the town, including five neighborhoods: Vila Nova, Sol Nascente, Centro, Green-Ville, and Arapiranga;
- Sector III – Açaí River sub-basins (tidal channels), in the northeastern part of the town, including only two neighborhoods: Arapiranga and Sol Nascente.

The morphology of the terrain is not uniform, due to the anthropogenic changes associated with the land occupation and drainage systems installation, whether by the public administration or local residents, which results in the overlapping of different materials. This formation of technogenic surface deposits not only reduces the capacity of ground infiltration and increases surface runoff, but also modifies the terrain topography, which may create focal points that direct the flow and accumulate rainwater on the streets, intensifying the effects of flooding (Luz et al., 2015).

The four phases of occupation of Vigia urban neighborhoods, defined by Bentes (2020), are integrated with the DTM and the orthomosaic to plot the occupation of the fluviomarine plain (Figure 6).

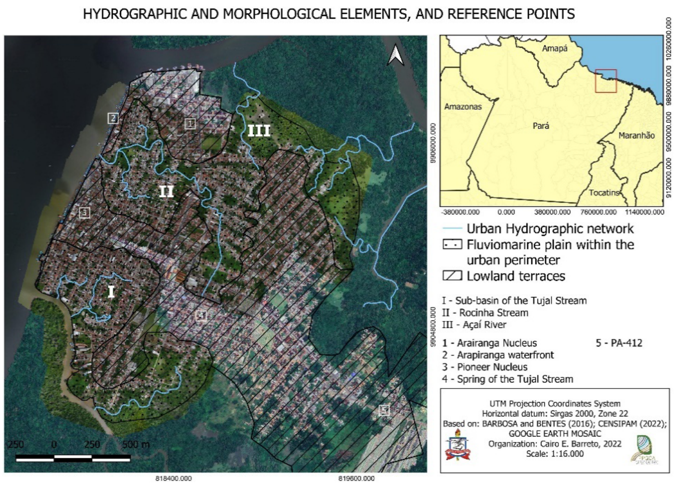

Figure 5 – The hydrographic and morphological components of the study area, and the reference points.
Source: Barreto (2022).

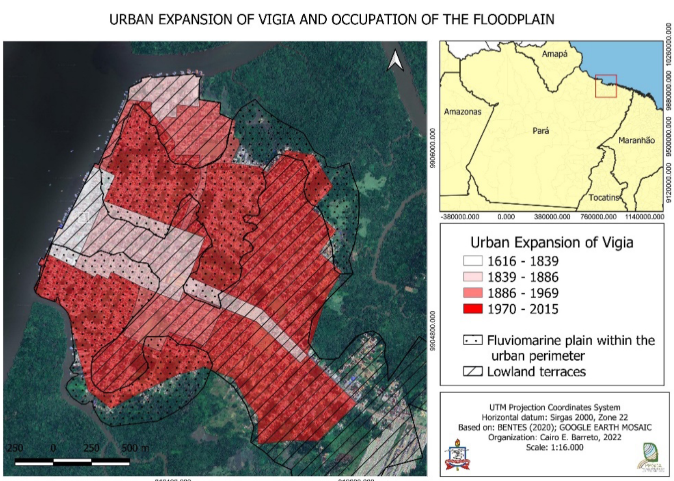

Figure 6 – Phases of the urban occupation of Vigia de Nazaré and the fluviomarine plain.
Source: Barreto (2022).

This analysis shows clearly that the plain, with some exceptions, was occupied about recently, that is, from 1960 onward, intensifying toward the end of the 1980s. Prior to this period, the occupation was limited almost entirely to the terrace, expanding only rarely into the low-lying marshlands, which are inappropriate for the local population's way of life. The four phases, which began after the 1970s, resulted in the present configuration of the town, as presented below.

The study total area of the polygon is approximately 3,402,554 m^2, of which 2,135,378 m^2 is lowland terrace, with altitudes of at least 4.5 meters above sea level, while the other 1,267,176 m^2 coincide with the floodplain. In other words, just over one-third of the urban center is constructed on the fluviomarine plain, which is directly affected by annual floods. This more recent and spontaneous occupation of the low-lying plains became the new vector of urban expansion, creating precarious settlements in response to the saturation of the town's central area.

This scenario imposes innumerable hydro-morphodynamic processes on the region all at the same time, due to the historical and economic drivers that contributed to the setting up of a vulnerable population. The occupation of this environment led to major physical alterations in an attempt to adapt to the reality of the local physical dynamics. Nevertheless, it hampered the implementation of necessary conditions for the establishment of an adequate way of life. Although there is no doubt that flooding is an inherent feature of the local environment, it has clearly been exacerbated by anthropogenic interventions (Canil et al., 2020). The occupation of these areas has also led to the suppression of the original role of the local waterways as a functional feature of the pre-urban existence of the local population, including the loss of important ecological services (Rodrigues, 2015), such as the economic use and navigation of channels, as well as the cultural and scenic heritage of the original environment (Santos, 2009).

Conclusions

Inherent vulnerability is a consequence of processes established by social and political drivers. The vulnerability of a given locality can be determined by the physical processes inherent to its environment, and its recent history of occupation. Vigia has features typical of an estuarine environment, which integrates oceanic and fluvial systems, adjacent to a dynamic tidal channel. The terrain is crisscrossed by small bodies of water and sub-basins that connect up to larger watercourses (Igarapé do Tujal, Rio Açaí, and Rio Guajará-Mirim). In addition, annual rainfall levels are extremely high.

In this scenario, there is a clear need for the implementation of adequate public policies of social assistance to limit the vulnerability of the population exposed to threats, as well as hydrometeorological hazard risks. It may be possible to change the existing reality through the application of directives of the municipal master plan that are aligned with sustainable development initiatives. New projects of urban development should also be implemented, such as the recuperation of permanent protection areas, and housing projects that target the population living in the areas of highest risk, providing adequate living conditions and access to the services of the urban zone. One example of this type of project is the "Vilenga Residential Initiative", which offered 280 housing units, with priority for "families resident in areas of risk or insanitary conditions, or that had been made homeless".

The monitoring of conditions, whether short- or medium-term (i.e. seasonal), will also be crucial for local risk management. In particular, more systematic studies on the influence of sea surface temperatures (SSTs) on rainfall patterns will be necessary, mainly during the rainy season, which is influenced by meteorological systems at a synoptic scale, and when the monitoring of the SST could provide a valuable indicator of flooding risk. Monitoring by the Belém meteorological radar, 75 km to the southwest, could also provide a mesoscale perspective on the local convection mechanisms, which are responsible for precipitation during the dry season.

Overall, given the intense local hydrodynamics, the fluvial channels located within the urban zone of Vigia may respond rapidly to almost any fluctuation in the hydrometeorological conditions of the system, which reinforces the need to install a Hydrological Data Collection Platform (HDCP) on the Guajará-Mirim River. It would also be essential to calibrate the terrain elevation with the tidal gauge or the HDCP, to generate models of flooding patterns. The "high tide and rain" warnings emitted by municipal authorities should also be improved through the integration of municipal social assistance and environment secretariats, firefighters, and other entities that can be mobilized at short notice to provide the population with assistance when floods occur.

Acknowledgments

We are grateful to the Pará State Coastal Management Observatory (OGCPará) for its academic and institutional support.

Contribution of authors:

BARRETO, C. E. C.: Conceptualization; Data Curation; Formal Analyses; Investigation; Methods; Validation; Writing. PIMENTEL, M. A. da S. P.: Supervision, Writing – review & editing.

References

Amanajás, J.C.; Braga, C.C., 2012. Padrões espaço-temporais pluviométricos na Amazônia Oriental usando análise multivariada. Revista Brasileira de Meteorologia, v. 27, (4), 423-434. https://doi.org/10.1590/S0102-77862012000400006.

Andrade, V.M.S. de; Cordeiro, I.M.C.C.; Schwartz, G.; Vasconcelos, L.G.T.R.; Oliveira, F. de A., 2017. Considerações sobre o clima e aspectos edafoclimáticos da Mesorregião Nordeste Paraense. In: Cordeiro, I.M.C.C.; Vasconcelos, L.G.T.R.; Schwartz, G.; Oliveira, F. de A. (eds.). Nordeste Paraense: panorama geral e uso sustentável das florestas secundárias. Belém: EDUFRA, p. 59-96.

Barbosa, E.J. da S., 2007. Unidades de Relevo em Zona Costeira Estuarina: municípios de Colares e Santo Antônio do Tauá (PA). Dissertação (Mestrado em Geografia), Instituto de Filosofia e Ciências Humanas, Universidade Federal do Pará, Belém, 96 p.

Barbosa, E.J. da S.; Bentes, L., 2016. Ocupação urbana em baixadas na Zona Costeira do estado do Pará: análise da cidade de Vigia de Nazaré. In: Bordalo, C.A.L.; Silva, C.N. da S.; Silva, E.V. da S. (eds.). Planejamento, conflitos e desenvolvimento sustentável em bacias hidrográficas: experiências e ações. Belém: GAPTA/UFPA, p. 509-542.

Barreto, C.E.C., 2022. As dimensões do risco hidrometeorológico na cidade de Vigia de Nazaré-Pa, Zona Costeira paraense. Dissertação (Mestrado), Universidade Federal do Pará, Instituto de Geociências, Belém.

Becker, B.K., 2001. Revisão das políticas de ocupação da Amazônia: é possível identificar modelos para projetar cenários? Parcerias Estratégicas, (12), 135-159.

Bentes, L., 2020. Rede Urbana e pequenas cidades da Amazônia: o caso de Vigia de Nazaré, PA. Thesis (Masters in Geography), Instituto de Filosofia e Ciências Humanas, Universidade Federal do Pará, Belém, 119 p.

Braga, R. da C.; Pimentel, M.A. da S.; Rocha, E.J.P., 2020. Mudanças climáticas e impactos da elevação do nível do mar na zona costeira: pesquisa bibliográfica e contribuição conceitual. Fronteiras: Journal of Social, Technological and Environmental Science, v. 9, (1), 230-255. https://doi.org/10.21664/2238-8869.2020v9i1.p230-255.

Brasil, 2022. Ministério do Desenvolvimento Regional. Secretaria de Proteção e Defesa Civil. Universidade Federal de Santa Catarina. Centro de Estudos e Pesquisas em Engenharia e Defesa Civil. Atlas Digital de Desastres no Brasil. Brasília: MDR (Accessed March 21, 2023) at:. http://atlasdigital.mdr.gov.br/.

Canil, K.; Lampis, A.; Santos, K.L. dos, 2020. Vulnerabilidade e a construção social do risco: uma contribuição para o planejamento na macrometrópole paulista. Cadernos Metrópole, v. 22, (48), 397-416. https://doi.org/10.1590/2236-9996.2020-4803.

Centro de Hidrografia da Marinha (CHM), 2002. Banco Nacional de Dados Oceanográficos. Observação de Maré. Nome da Estação: Fábrica ECOMAR. Initial date: 05/12/2002; final date: 06/12/2002. Niterói: CHM.

Centro de Previsão de Tempo e Estudos Climáticos (CPTEC), 2022. Instituto Nacional de Pesquisas Espaciais (Accessed in January 2022) at:. http://enos.cptec.inpe.br/.

Clemente de Lacerda, I.L.; Amaro, V.E.; Matos, M. de F.A.; Scudelari, A.C., 2022. Physical vulnerability of the coastal zone under wind farms influence of the cities of Pedra Grande and São Miguel do Gostoso/RN, Brazil. Brazilian Journal of Environmental Sciences, v. 57, (3), 422-433. https://doi.org/10.5327/Z2176-94781244.

Cohen, J.C.P.; Silva Dias, M.A.F.; Nobre, C.A., 1995. Environmental conditions associated with Amazonian squid lines: a case study. Monthy Weather Review, v. 123, (11), 3163-3174.

Collischonn, W.; Dornelles, F., 2013. Hidrologia para Engenharia e Ciências Ambientais. Porto Alegre: ABRH.

Cruz Primo, V.H.; Rafaeli Neto, S.L., 2023. Assessment of economic impacts in flood events in Lages/SC, Brazil. Brazilian Journal of Environmental Sciences, v. 58, (1), 30-44. https://doi.org/10.5327/Z2176-94781486.

Dietrich, G, 1963. General Oceanography: an introduction. New York: Interscience.

Espinoza, J.C., Ronchail, J., Marengo, J.A., Segura, H., 2019. Contrasting North–South changes in Amazon wet-day and dry-day frequency and related atmospheric features (1981–2017). Climate Dynamics, v. 52, 5413-5430. https://doi.org/10.1007/s00382-018-4462-2.

Fernandez, G.; Rocha, T., 2022. Temas e Conceitos da Geomorfologia Costeira e do quaternário nas perspectivas histórica e das mudanças ambientais. In: Guerra, A.; Loureiro, H. (eds.). Paisagens da Geomorfologia Bertrand Brasil, 376 p.

Ferreira, D.B. da S., Souza, E.B. de S., Moraes, B.C. de M., Meira Filho, L.G., 2015. Spatial and Temporal Variability of Rainfall in Eastern Amazon during the Rainy Season. The Scientific World Journal, v. 2015, 209783. https://doi.org/10.1155/2015/209783.

França, C.F.F.; Souza Filho, P.W.M., 2003. Análise das mudanças morfológicas costeiras de médio período na margem Leste da Ilha de Marajó (PA) em imagem Landsat. Revista Brasileira de Geociências, v. 33, (2), 127-136.

Girão, Í.R.F.; Rabelo, D.R.; Zanella, M.E., 2018. Análise teórica dos conceitos: Riscos Socioambientais, Vulnerabilidade e Suscetibilidade. Revista de Geociências do Nordeste, v. 4, 71-83. https://doi.org/10.21680/2447-3359.2018v4n0ID13273.

Gomes, V.J.C.; Asp, N.E.; Siegle, E.; McLachlan, R.L.; Ogston, A.S.; Silva, A.M.M.; Nittrouer, C.A.; Souza, D.F., 2020. Connection between macrotidal estuaries along the southeastern Amazon coast and its role in coastal progradation. Estuarine, Coastal and Shelf Science, v. 240, 106794. https://doi.org/10.1016/j.ecss.2020.106794.

Hayashi, S.N.; Souza-Filho, P.W.M.; Nascimento, W.R. Jr.; Fernandes, M.E.B., 2019. The effect of anthropogenic drivers on spatial patterns of mangrove land use on the Amazon coast. PLoS One, v. 14, (6), e0217754. https://doi.org/10.1371/journal.pone.0217754.

Instituto Brasileiro de Geografia e Estatística (IBGE), 2009. Manual técnico de geomorfologia. 2. ed. Rio de Janeiro: Coordenação de Recursos Naturais e Estudos Ambientais do IBGE, 182 p. (Manuais técnicos em Geociências, n. 5).

Instituto Brasileiro de Geografia e Estatística (IBGE), 2011. Atlas geográfico das zonas costeiras e oceânicas do Brasil. Rio de Janeiro: Diretoria de Geociências do IBGE, 176 p.

Instituto Brasileiro de Geografia e Estatística (IBGE), 2021. IBGE. Sidra: Banco de Tabelas Estatísticas (Accessed October, 2021) at:. https://sidra.ibge.gov.br/home/.

Instituto de Pesquisa Econômica Aplicada (IPEA), 2016. Caracterização e tipologia de assentamentos precários: estudos de caso brasileiros. Brasília: IPEA.

Intergovernmental Panel on Climate Change (IPCC), 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, pp. 3-32. https://doi.org/10.1017/9781009157896.001.

Ishiwatari, M.; Surjan, A., 2019. Good enough today is not enough tomorrow: Challenges of increasing investments in disaster risk reduction and climate change adaptation, Progress in Disaster Science, v. 1, 100007, ISSN 2590-0617, https://doi.org/10.1016/j.pdisas.2019.100007.

Kjerfve, B., 1990. Manual for investigation of hydrological processes in mangrove ecosystems. Nova Déli: UNESCO/UNDP, 79 p.

Lima, M.W. de; Santos, M. de L.S.; Melo, N.F.A.C. de; Faial, K. do C.F.; Lima, M. de O.; Nunes, D.M., 2015. Distribuição espaço-temporal dos metais Ba, Na, K, Mn e Ca nos sedimentos de fundo do estuário Furo da Laura, Amazônia Oriental, Brasil. Boletim Técnico Científico do CEPNOR, v. 15, (1), 15-22. https://doi.org/10.17080/1676-5664/btcc.v15n1p15-22.

Lopes, M., 2016. Modelagem Hidrodinâmica 2DH no Furo da Laura-Nordeste Paraense. Belém-PA, 2016. 76 f. Dissertação (Mestrado em Geofísica), Instituto de Geociências, Universidade Federal do Pará, Belém.

Luz, L.M. da; Rodrigues, E.C.; Ponte, F.C. da; Silva, C.N. da, 2015. Impactos antropogênicos em bacias urbanas da área central da cidade de Belém-PA. In: Bordalo, C.A.L.; Silva, C.N. da; Silva, E.V. da (eds.). Planejamento, conflitos e desenvolvimento sustentável em bacias hidrográficas: experiências e ações. Belém: GAPTA/UFPA, p. 439-509.

Marengo, J.A.; Nunes, L.H.; Souza, C.R. de G.; Hosokawa, E.K.; Pedro, G.R.; Harari, J.; Moreira, P.F.; Franco, P.L.; Bandini, M.P.; Garcia, P.D.; Gireli, T.Z., 2022. Risk management and vulnerability to sea level rise in Brazil, with emphasis to the legacy of the Metropole Project in Santos. Derbyana, v. 43, e768. https://doi.org/10.14295/derb.v43.768.

McKee, T.B.; Doesken, N.J.; Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society, p. 179-183.

Miranda, T.B., 2020. A ilusão da igualdade: natureza, justiça ambiental e racismo em Belém. Supervisor: Ana Cláudia Duarte Cardoso. Thesis, ITEC, UFPA, Belém, 205 p.

Mussi, C.S.; Zago, N.I.; Marenzi, R.C.; Polette, M., 2022. Environmental sensitivity analysis of environments affected by the oil spill on the Brazilian coast. Brazilian Journal of Environmental Sciences, v. 57, (4), 644-653. https://doi.org/10.5327/Z2176-94781441.

National Weather Service (NOAA), 2022. Climate Prediction Center – CPC (Accessed in January 2022) at:. https://www.cpc.ncep.noaa.gov/.

Nina, A.S.; Szlafsztein, C.F., 2018. As Inundações de 2009 Na Amazônia e Suas Relações Com o Desenvolvimento Sustentável: Impactos ao Produto Interno Bruto Municipal. Geographia, v. 20, (43), 101-123. https://doi.org/10.22409/geographia2018.v20i43.a27214.

Oliveira, R.C. de, 2010. Dinâmica de funcionamento da paisagem e relações de ocupação e risco de movimentos de massa e inundações: cenários da região da Baixada Santista no estado de São Paulo e das costas do cacau e do descobrimento no estado da Bahia, Brasil. Revista Territorium, (17), 151-160. https://doi.org/10.14195/1647-7723_17_16.

Palheta, I.G. de V., 1980. O uso da terra em Tauá-Vigia, estado do Pará. 1980. 167 p. Dissertation (Doctorate in Geography), Department of Geography, Universidade de São Paulo, São Paulo.

Pinkayan, S., 1966. Conditional occurrence of wet and dry years over a large continental area. Colorado: State University; Boulder-Co. (Hydrology papers, n. 12).

Prefeitura de Vigia de Nazaré, 2020. Alerta de Maré Alta em Vigia em 11 de março de 2020 (Accessed August 20, 2022) at:. https://vigia.pa.gov.br/aviso-mare-alta/.

Rodrigues, C., 2015. Atributos ambientais no ordenamento territorial urbano: o exemplo das planícies fluviais na metrópole de São Paulo. Geousp – Espaço e Tempo, v. 19, (2), 325-348. https://doi.org/10.11606/issn.2179-0892.geousp.2015.102805.

Santos, J.P.S. dos, 2009. Vigiando a cidade: um olhar contemporâneo sobre a sociedade e o espaço no município de Vigia. Vigia: Editora da BPAV, 98 p.

Santos, M.R.S.; Vitorino, M.I.; Carneiro, L.C.C., 2019. Spatiotemporal Variation in the Precipitation of the Amazon Coastal Zone: Use of Remote

Sensing and Multivariate Analysis. Revista Brasileira de Climatologia, v. 25, 35-53. https://doi.org/10.5380/abclima.v25i0.64892.

Santos, S.R.Q.; Braga, C.C.; Sansigolo, C.A.; Santos, A.P.P., 2017. Determinação de Regiões Homogêneas do Índice de Precipitação Normalizada (SPI) na Amazônia Oriental. Revista Brasileira de Meteorologia, v. 32, (1), 111-122. https://doi.org/10.1590/0102-778632120160013.

Souza, J.O.P. de, 2013. Dos sistemas ambientais ao sistema fluvial – uma revisão de conceitos. Caminhos de Geografia, v. 14, (47), 224-233. https://doi.org/10.14393/RCG144722281

Tricart, J., 1977. Ecodinâmica. Rio de Janeiro: IBGE; SUPREN, 97 p.

Trindade Jr., S-C.C., 2018. (Re)invenções urbanas na Amazônia: Belém do Pará, metamorfoses de uma cidade quadricentenária. In: Sposito, M.E.B.; Fernandes, J.A.R. (eds.). Brasil e Portugal vistos desde as cidades: as cidades vistas desde os seus centros. São Paulo: Cultura Acadêmica, v. 1, p. 293-316.

Trindade Jr., S-C.C., 2022. Urbanodiversidade e pensamento crítico contemporâneo: reflexões a partir das cidades amazônicas. In: Pacifico Filho, M. (ed.). Urbanodiversidade: possibilidades e contradições. Palmas: EdUFT.

Tucci, C.E.M., 2012. Hidrologia: ciência e aplicação. 4. ed. Porto Alegre: ABRH, 944 p.

Villar, J.C.E., Ronchail, J.; Guyot, J.L.; Cochonneau, G.; Naziano, F.; Lavado, W.; Oliveira, E.; Pombosa, R.; Vauchel, P., 2009. Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador). International Journal of Climatology, v. 29, (11), 1574-1594. https://doi.org/10.1002/joc.1791.