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Comparing the Effects of Erosion and Accretion along the Eastern Coast of Río de Janeiro and Guanabara Bay in Brazil

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Abstract: This paper presents a case study of a general research project investigating the coastal landscapes' evolution in different port cities of the American continent with a common historical background: colonization. The general aim is to ascertain whether the evolution of coastal landscapes in the selected port cities is influenced by the origins of their colonizers, who initiated changes that shaped these cities into repositories of artistic, cultural, and historical heritage. The paper presents a study of the coastal landscape transformation in Rio de Janeiro and Guanabara Bay, Brazil. The study employs a comparative approach, utilizing cartographic maps from disparate historical periods, with the objective of identifying and quantifying changes in the coastline. The results indicate that accretion exceeded erosion over the study period. The erosion is associated with the loss of mangroves, underscoring the necessity for environmental protection and reconstruction efforts in affected regions. The research contributes to the existing body of knowledge by providing a comprehensive analysis of the coastal transformation in Rio de Janeiro and Guanabara Bay and its impact on the environment. Furthermore, it allows for a comparison with the port cities of the other case studies in the overall research.

Keywords: Rio de Janeiro; Guanabara Bay; littoral; coastline; colonial cartography; aerial photography; accretion; erosion

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1. Introduction

The coastline is the boundary between the land and the ocean or sea. Its nature depends on the coastal geomorphology, climate, vegetation protection, and human activities, which together influence soil stability and its ability to decompose and become particles transported along the coast [1]. The transportation of material involves the movement of particles from their original location to a deposition site, resulting in the accumulation of material at the receiving beach and the erosion of material at the original site. Erosion and accretion are natural processes that occur on shorelines over various time scales. These changes are influenced by a number of factors, including short-term events such as storms, waves, tides, and winds, as well as long-term events such as glaciation, sea level changes, and tectonic activities that can cause coastal subsidence or emergence [2].

Coastlines are naturally dynamic entities engaged in a continuous interaction between the ocean and the continent. The ocean exerts a profound influence on the continent, modifying its morphology through processes of erosion or accretion. The receding water transports material back to the coastline, perpetuating this cycle. This dynamic interaction depends on the initial nature and morphology of the coastal zones. It is important to distinguish between structural coasts (cliffs, reefs, flats) and sedimentary coasts (various beach shapes influenced by structural morphology) [3]. The environmental dialectic results in a dynamic equilibrium where coastal erosion and recovery occur in cycles influenced by the maritime climate, ranging from daily to decadal. In order for sediment changes to be considered erosion or deposition, they must persist beyond the aforementioned cycles. Any coastal losses that are not recovered within a decade are considered to be permanent and indicative of a coastal imbalance.

The aim of this research is to examine the coastal region of the east part of Rio de Janeiro and Guanabara Bay in Brazil, which has historical significance as a site where the transformation of the landscape from its original state to a constructed one can be observed. This transformation was the result of direct human action, and after excessive human intervention, the landscape in some areas was severely damaged, demonstrating the necessity for its reconstruction. The degree of landscape transformation was quantified in areas where the most significant anthropogenic impact was observed, with the results classified as either erosion or accretion. In addition to the aforementioned considerations, other aspects related to landscape transformation were also evaluated, including the potential implications of land use and various practices on the landscape and future developments. This paper presents a case study of a general research project investigating the evolution of coastal landscapes in various city ports across the American continent. The general research examines the impact of anthropogenic actions, including land use changes, environmental policies, customs, and other factors, on the coastal landscape from the colonial era to the present.

As has already been studied by this research group, there are four phases in the perception of the physical environment to understand and to shape the ecosystem and turn it into a territory, to transform it from a "site" into a "place"; these being submission, adaptation, conquest, and respect. The following definitions will be used by González et al. [3].

Submission phase: Humans fear nature, and cities are built away from the sea's shoreline to be protected from storms and rough weather whilst also watching out for pirates and preventing invasions.
Adaptation phase: After humans become sedentary by observing nature, modifying its customs, and natural resources are optimized and begin to coexist within the framework of the city.
Conquest phase: Humanity has knowledge, training, tools, and technology at its disposal to overcome obstacles imposed by the environment and take over the territory. In some cases, this leads to the disappearance of plant and animal species.
Respect phase: Implies greater awareness for a life in equilibrium with the environment, where engineering must be managed based on environmental sensitivity and social equity.

This paper is part of a larger body of research that examines the relationship between the four phases of perception of the physical environment described above and the four states of the landscape. To understand this relationship, it is essential to identify the differences between the four following named states: original, constructed, destroyed, and reconstructed landscapes. This paper will use the following definitions, which were developed by Martín [4] within the context of the littoral panorama.

Original landscape: The concept is to defend exceptional places within an objective concept and dimension. It responds to the concept of "protected" in certain bibliographic sources.
Constructed landscape: The concept combines nature and construction works, illustrating the evolution of the natural environment as a social and cultural force. It responds to the concept of "cultural" in certain bibliographic sources.
Destructed landscape: "Abandoned". This consists of the disappearance of the natural and territorial area of the city and nature in all its aspects, from social to environmental, from sustainable to communications.
Reconstructed landscape: It consists of rehabilitating, dismantling, and returning the "place" to its exceptional and objective scenario and horizon "reconquered".

Coastal Erosion

Coastal erosion is the result of human activities and natural changes that disrupt the balance of coastal dynamics, including waves, currents, and wind—long-term sediment loss results in a retreat of the coastline and beach erosion [5]. Two conditions must be met for coastal erosion to occur: a strong current flow that moves the bottom sediment and an imbalance between the sediment supply and loss. In order to prevent further erosion, it is necessary to analyze the mechanisms that give rise to these conditions [6].

Coastal Accretion

Coastal accretion is defined as the process by which sediments accumulate at a specific coastal location, resulting in a shift of the coastline seaward. This phenomenon can occur naturally or as a result of human activities, such as the direct deposition of sand to widen beaches or the construction of ports and artificial islands. Precisely, Martín et al. [7] show that land reclamation, particularly for the purpose of constructing harbors, is a pervasive phenomenon, predominantly in China, Japan, Korea, and the Persian Gulf.

Study Area

Rio de Janeiro, established in 1563, is a city with a rich historical legacy and a port serving as the capital of the state of Rio de Janeiro in Brazil. The city of Rio de Janeiro is situated on the Atlantic coast in southeastern South America, between the longitudinal coordinates 43°00′00″ and 43°20′00″ W and latitudinal coordinates 22°40′00″ and 23°05′00″ S. Its coastline and Guanabara Bay feature a distinctive habitat formed by the interaction between Atlantic Forest species and oceanic sand plains, locally known as restingas (sand spit) [8]. These restingas (sand spits) are formed by the process of sediment deposition along the coastal plains of the seas and oceans. The sediments, particularly sand, which constitute the limestone soils of this ecosystem, were deposited primarily by the action of ocean water.

The morphology of the coastline presented changes during the Quaternary period (late Pleistocene and early Holocene) due to sea level variations resulting from glaciations and interglacial periods in which global warming occurred [9]. These changes included the formation of inland salt lagoons resulting from the closure of primitive bays or coves of small to medium size, as well as the development of dune lines parallel to the coast.

This work was developed on a littoral area formed by the Guanabara Bay (Figure 1), which extends along the east coast of Rio de Janeiro City, south of Duque de Caxias, Magé y Guapimirim, and along the coast of Sao Gonçalo and Niteroi.

Guanabara Bay is one of the largest on the Brazilian coast, with an area of approximately 384 km^2, 131 km of coastline (94 km to this research boundaries), and a mean water volume of 1.87 × 109 m^3 [10]. It is one of Brazil's most important bays due to its growing shipping activity. This is driven by both foreign and domestic trade, as well as oil and gas operations. The bay's supply vessels and tankers handle nearly 20% of all Brazilian imported oil [11]. The total length of this study's coastline is approximately 331 km (Table 1), which corresponds to the inner coastline of the bay, the coastlines of the islands located within the bay, the Copacabana coastline, and the coastline leading to Piratininga beach, situated southeast of the bay. The Copacabana coastline is also under the jurisdiction of the State of Rio de Janeiro, yet it is exposed to the action of the Atlantic Ocean in an unobstructed manner. The continental coastline is approximately 232 km in length, while the coastline of the islands is approximately 99 km.

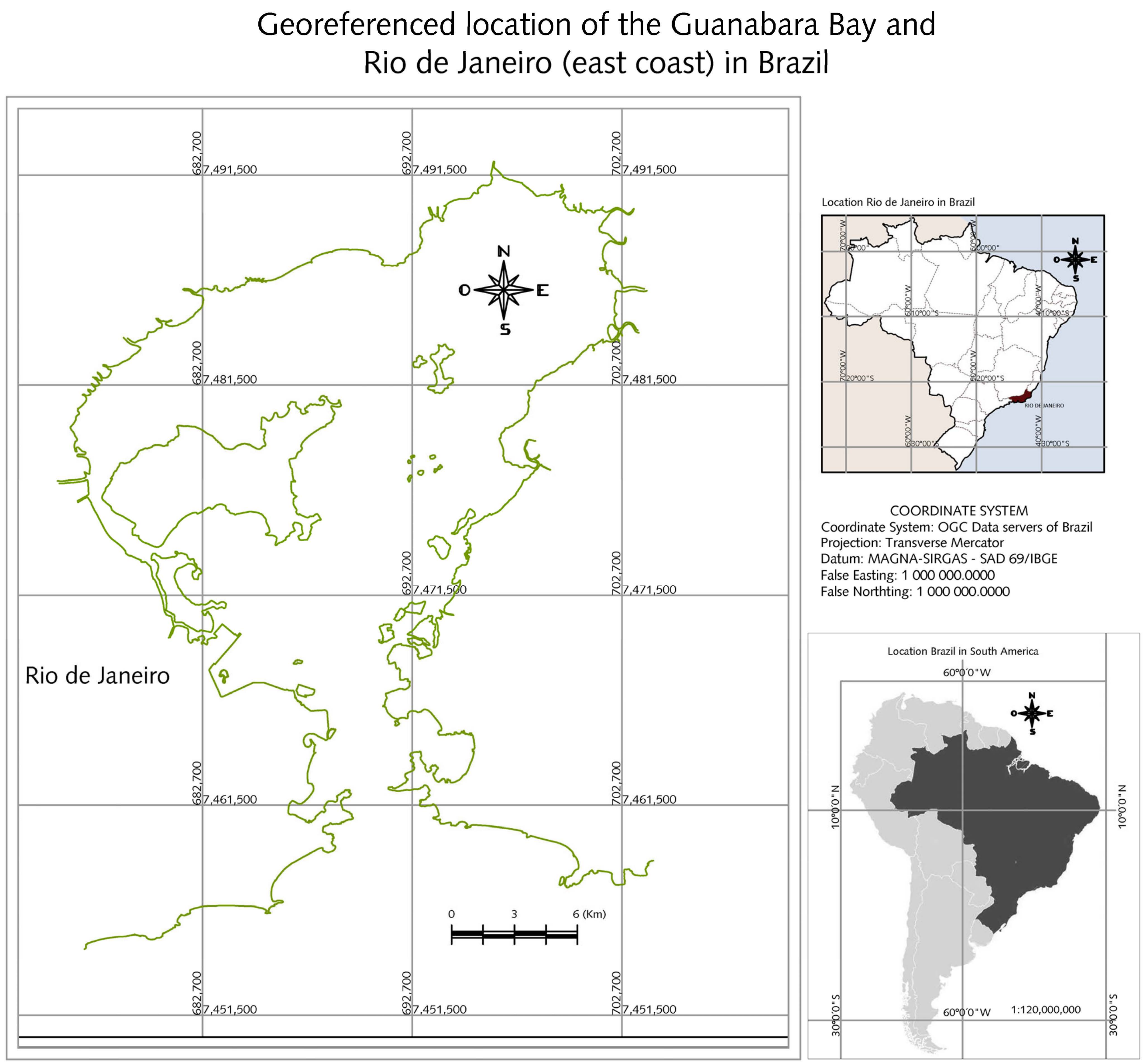

Figure 1. Georeferenced location (plane coordinates) of Guanabara Bay in the S of Brazil. Brazil is located in South America at the bottom right (geographic coordinates). Elaborated with QGis v3.4.8. OGC data servers of Brazil. Brazil's official reference system (datum) is the MAGNA-SIRGAS—SAD 69/IBGE.

Table 1. Coastline, study length. Source: Own compilation 2022.

Study Length (Coastline 2022) [km]				
Piratinga—Niteroi—Sao Gonzalo	Continent	82	100	
Piratinga—Niteroi—Sao Gonzalo	Island	18		
Northeast Guanabara Bay	Continent	82	94	331
Northeast Guanabara Bay	Island	12		
D. Caxias—Copacabana Beach	Continent	68	137	
D. Caxias—Copacabana Beach	Island	69		
Continent		232	331	
Island		99		

According to Canedo de F. Pinheiro, E. [12], geological and geographical research indicates that approximately 10,000 years ago, the sea level was approximately 130 m lower than it is today [13]. Over millennia, the submerged continental shelf has undergone significant changes. During this period, the area has been subject to the formation of resting areas (sand spits: sandy coastal vegetation), cliffs, and dunes. This landscape was home to a diverse array of megafauna, including mastodons, saber-toothed tigers, giant armadillos, and six-meter-long sloths [14]. The disappearance of these animals remains uncertain. One hypothesis is that it was due to food shortages during the last ice age. Another is that they were unable to survive the rising Atlantic Ocean waters on the continental shelf. Nevertheless, approximately 12,000 years ago, the flooding event resulted in the formation of Guanabara Bay [15]. Conversely, the bathymetry of the bay has undergone significant modifications since its inception. Studies conducted by Kjerfve et al. [16] indicate the presence of a central channel with a depth of 30 m. However, Araruna et al. [11] have identified the occurrence of extensive mud deposits within the interior parts of the bay, which they attribute to the accelerated transport of fluvial clastic materials to the bay as a result of anthropogenic activities in the drainage basin. The active transport of fluvial clastic materials to the bay, accelerated by anthropogenic activities in the drainage basin, has resulted in a bay-averaged water depth of 5.7 m. According to Muehe et al. [17], the average depth of the bay is approximately 3 m in its most inland section, 8 m in its central part, and 17 m in the entrance channel. Figure 2 was obtained using a Chart Viewer tool, a platform developed and managed by Navionics, Inc., and Navionics S.r.l. This figure shows the bathymetric map of the entrance channel to the bay. The channel exhibits a depth of up to 50 m in select locations. However, as one progresses further to the bay's banks, the depth gradually diminishes to an average of 30 m at the channel. This reduction in depth persists until it reaches the coastline.

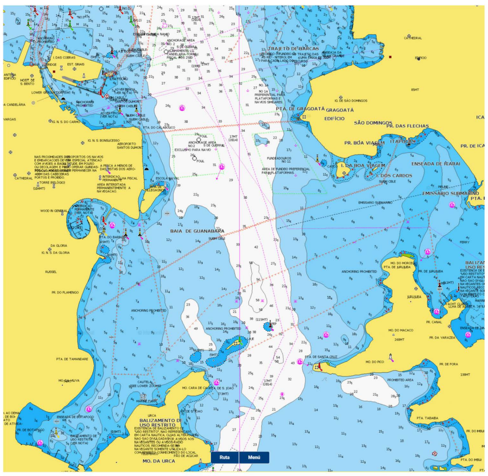

Figure 2. Bathymetric map of the entrance channel to Guanabara Bay. Source: Navionics, Inc. and Navionics S.r.l.

The sedimentary mineralogy of the interior of Guanabara Bay is predominantly composed of sand grains with a spheroidal shape, primarily consisting of quartz, feldspar, and amethyst. Furthermore, the sedimentary deposits include calcareous shells in the form of plates of varying sizes. The sedimentary deposits from the southeastern region of Governador Island exhibit a higher density than those from the northwestern region [11].

The beaches of Guanabara Bay are located in a low-wave energy environment, protected from high-energy events but not immune to them. The beaches closest to the entrance of the bay, or positioned in front of the wave entrance, are dynamic and even vulnerable to wave energy. The others, located at the bottom of the bay, have very low dynamics [18]. In the inner bay, storm effects are sporadically felt at Flamengo and Botafogo inlets and at Ingá and Icaraí shores in Niteroi. At Ilha do Governador, the east-facing shore suffers some effects of the local wave action generated by the northeast wind associated with water piling that may flood the beach shore. In general, however, the interior of the bay is protected, mainly from the action of southeast storm waves [19].

In the case of beaches in densely urbanized and modified urbanized regions, sand can spill onto sidewalks and avenues, causing damage such as the breakage of buried pipes and the destruction of sidewalks and other public assets. When cleaning streets and sidewalks, sand is not always returned to the environment, which, in the long term, can lead to a decrease in sand reserves and create a tendency to erosion. The most frequent undertows occur between the months of March and August along this part of the coast (Niteroi), according to historical records dating back some 107 years [20]. On some occasions, the swells that hit Guanabara Bay cause a beautiful spectacle of high and successive waves, suitable for surfing. One of them was recorded by the Surfar Magazine team (May/June 2010) on 8 April 2010, when the bay was hit by southeast swells with periods of 12 and 13 s, which, upon entering the bay, caused waves of 5.5 to 5.8 m in height. On this occasion, as in other works, such pipelines and boardwalks were damaged [19].

The wave climate that characterizes the south coast is conditioned by frequent changes in wind conditions, associated with the passage of cold fronts and the constant presence of swells generated by storms in the high latitudes of the South Atlantic and dissociated from the local wind [21] cites; as an example of extreme cases, for Rio de Janeiro, periods of swells from the south quadrant from 10 to 16 s with significant heights of up to 4 m.

The climate of Rio de Janeiro state is tropical, with year-round rainfall peaking in the summer, which also experiences the highest temperatures. The coastal climate is influenced by two meteorological phenomena: the Atlantic Tropical High-Pressure Mass, which brings hot and humid conditions and intense summer heat, and the Atlantic Polar Mass, which brings cold conditions, especially from May to September, causing sharp temperature drops that can last up to a week [22].

The State Institute of Environment of Rio de Janeiro (State Institute of the Environment—INEA) used data collected over three years to perform the water quality analysis. With limited sampling, the results of Figure 3 show that the mouth of Guanabara Bay (Region 2) was the region with the highest score (71%); this area includes regions near the coast at the mouth of the bay on both the western (Rio de Janeiro) and eastern (Niteroi) sides. The central channel (Region 1) was the second highest scoring region (65%), as this region has high oceanic scour in the deep central channel of the bay, which extends from the oceanic entrance of the bay to Paquetá Island. Oceanic scour helps remove nutrients and sediments from this region and keeps dissolved oxygen levels high. However, the central margins of Guanabara Bay (Region 3) achieved an average overall score (56%) due to the presence of the ports of Rio de Janeiro and Niteroi, which are situated in dredged channels and are affected by the presence of boats. The region north of Guanabara Bay (Region 4) achieved the second lowest score (47%), which was attributed to the shallow water and mangrove habitats from the mouth of the Iguaçu River to Itaoca, which are subject to numerous pollution inputs that increase nutrient levels and decrease dissolved oxygen. Finally, the northwest of Guanabara Bay (Region 5), situated west of the mouth of the Iguaçu River, was the lowest scoring region (19%), generated by the channels separating Governador and Fundao islands. These channels contain excess pollution and degradation due to their poor circulation and shallow depth [23].

Historical Description of Study Area

The Guanabara region was first inhabited by "sambaquis men" around 2 million years ago during the Pleistocene, followed by the Tapuias, and later by the Tupi or Tupi-Guarani (specifically the Tupinambás) until the Europeans arrived in the 16th century. At that time, the Tupinambás population was about one million, with approximately 15,000 Tamoios living along Guanabara Bay. The Portuguese, led by Gaspar de Lemos, arrived in Rio de Janeiro on 1 January 1502, and named the city port after their landing date. During colonization, the Portuguese often clashed with the French, who tried to claim part of the territory, leading the Portuguese to construct defenses to protect their coasts [24].

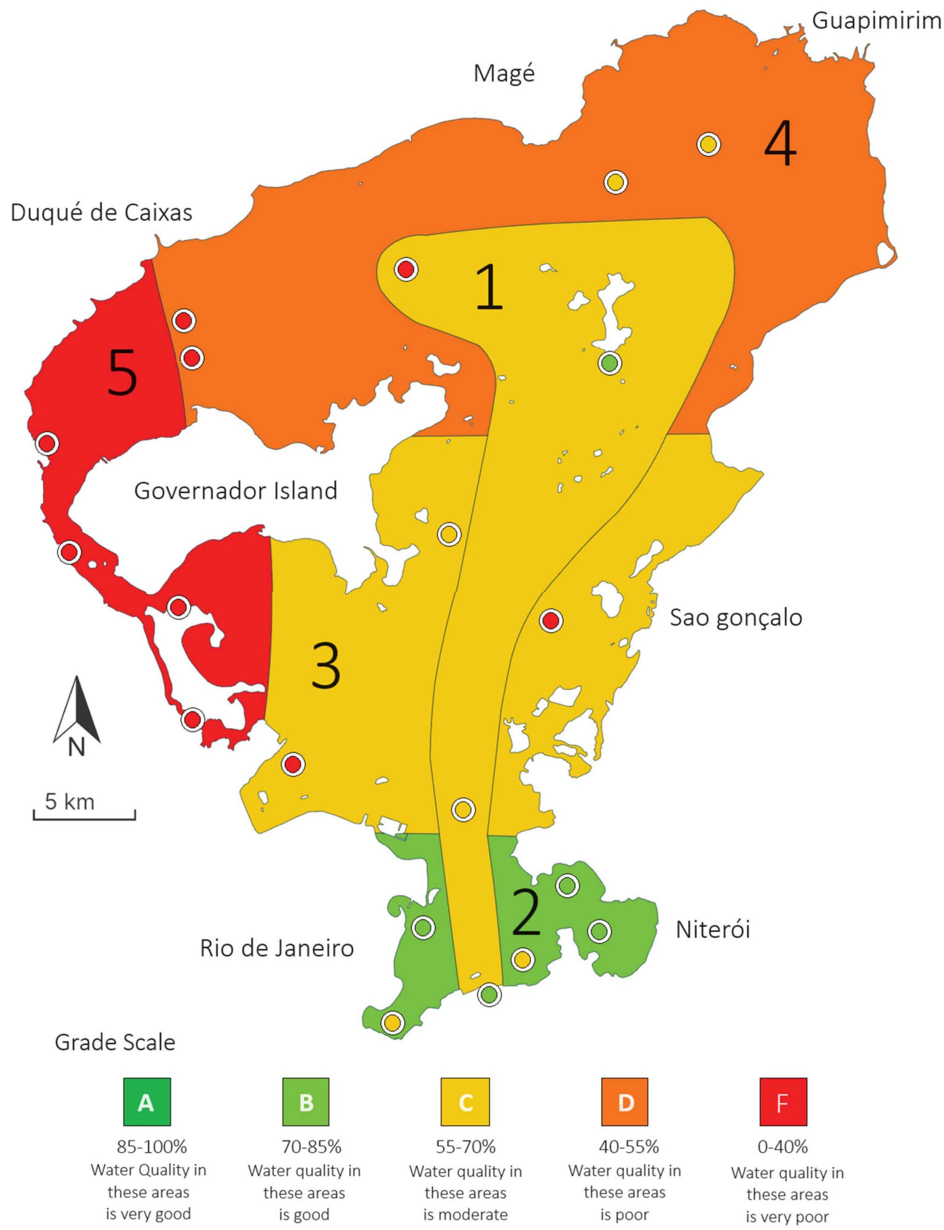

Figure 3. Water quality of Guanabara Bay. Source: The State Institute of Environment of Rio de Janeiro (INEA) [23].

In Brazil, as in numerous other colonies, the economic model that emerged during the initial centuries of Portuguese rule was centered on the extraction of natural resources. Common activities included the harvesting of brazilwood ("Ibirapitanga" or "pau-brasil") for dyes and whaling. All parts of the whales were utilized for various purposes, including food and construction. Furthermore, the Europeans perceived the necessity to subdue the local environment despite its perceived beauty. This was due to the presence of enemy indigenous tribes, fierce and poisonous animals, frightening storms, intense heat, and insects that transmitted unknown tropical diseases [12].

The cultivation of sugar cane and the slave trade brought significant wealth to Brazil, leading to the occupation of inland areas along the riverbanks used to transport sugar to Europe via Rio de Janeiro. In the early 19th century, the invasion of the Iberian Peninsula by Napoleon prompted Prince Regent Juan de Braganza to relocate the Portuguese court to Brazil. This resulted in Rio de Janeiro becoming the capital of the Portuguese Empire. Following the Queen's demise, Juan ascended to the imperial throne as Emperor João VI, presiding until his abdication in favor of his son Pedro I. Pedro I, in turn, declared Brazil's independence on 7 September 1822. In 1831, Pedro I abdicated the throne in favor of his son, Pedro II, who ruled for nearly fifty years and implemented significant changes in Rio de Janeiro. The abolition of slavery gave rise to a new Republican movement, which ultimately led to a military coup on 15 November 1889, resulting in the emperor's exile. Subsequently, Rio de Janeiro became the capital of the newly established government. In the early 20th century, Prefect Francisco Pereira Passos implemented a beautification and sanitation plan, which included the construction of a new port and the transformation of the city's coastline. The influx of individuals from rural areas resulted in the emergence of the inaugural "favelas" on the hillsides. In the early 21st century, the evolving needs of the city's inhabitants and visitors have driven continuous change.

Evolution of the Littoral Landscape of Study Area

The coastal landscape of Rio de Janeiro underwent the following three principal phases of evolution: initial fortification during the colonial period, technical and aesthetic improvements by the Portuguese Empire, and later developments in the republican period. As a strategic hub between Europe and South American ports, Rio de Janeiro attracted settlers who exploited tropical resources along the rivers of the Baixada Fluminense region, using these waterways for local and export transport. Over time, the accumulation of sediments in Guanabara Bay resulted in a reduction in navigability. The population growth that occurred in the 19th century resulted in a significant erosion of the bay's shoreline, the destruction of mangroves and swamps, and the disruption of the bay's environmental balance. The construction of the Port of Rio de Janeiro and the drainage of mainland lagoons contributed to the exacerbation of urban flooding. The deforestation of the Atlantic Forest resulted in the clogging of rivers, thereby reducing their connectivity with the city. Consequently, rail and later automobile connections were established to maintain links between the residents of Rio de Janeiro and those of the surrounding region [25].

The western coast of the bay was not a continuous line of land in the 18th century. Rather, it was the result of the filling that occurred in the latter half of the 19th century. The initial formation of this part of the coastal bay was the result of the construction of islands and small sacs (small coves) in the towns of Gamboa, Saúde, Santo Cristo, and Caju, particularly between Morro da Conceição and Saúde. This was a response to the incursions of French corsairs in the bay.

The coastline of Rio de Janeiro underwent significant alterations in the early nineteenth century as a consequence of the growing popularity of sea bathing. This practice subsequently gained significant traction following the arrival of the Royal Family in 1808. In the nascent stages of the practice, sea bathing was conducted in locales such as Caju Beach and Santa Luzia Beach. In the early nineteenth century, a bathhouse was constructed at Caju Beach for Prince D. João VI, and the inaugural royal beach hotel was established there. Santa Luzia Beach, which had previously been a neglected area due to the presence of nearby facilities that were considered undesirable, began to improve in 1852 with the inauguration of a hospital and the relocation of a cemetery. In 1859, the German Gymnastics Society was established at Santa Luzia Beach, and the area subsequently became a popular destination for regatta clubs and sea bathing. The inaugural Brazilian hotel, Hotel Pharoux, was constructed in 1814 in the vicinity of the present-day Praça XV. During the colonial period and into the early 19th century, the Valongo dock in this region served as a warehouse for slaves and salt [26].

The Copacabana neighborhood in Rio de Janeiro's southern region was originally a vast, arid expanse of sand known to the Tupi Indians as soco-apê-nupã. The transformation of the area commenced at the end of the nineteenth century, particularly following the construction of the Old Tunnel in 1892, which connected Botafogo and Copacabana. The Pereira Passos Reform facilitated greater accessibility to the open beaches in the South Zone, while the incorporation of those beaches into the port area rendered sea bathing in the city center impractical [27]. To the south of these desolate beaches, the Copacabana Fort was constructed at the beginning of the 20th century and served as a defensive system for the city of Rio de Janeiro and its port. The construction of the structure was completed in 1914. From this point to Ponta do Leme, the Copacabana coastline is developed, largely articulated by the Avenida Atlantica.

At the beginning of the 19th century, the coastline of Rio de Janeiro's Central Zone, situated between the present city center and the Botafogo embayment, underwent a significant transformation. The process of land reclamation resulted in the extinction or modification of several beaches. The damage caused by sea storms at beaches such as Saúde and Glória led to further coastal works being undertaken. In the early 20th century, the sinuous coastline with small gulfs and pocket beaches was replaced by a straightened, walled shoreline, which eliminated sandy areas and sea bathing spots. This transformation facilitated the renovation of the port and the construction of Avenida Beira Mar, which commenced in 1906 as part of Mayor Pereira Passos' reform. The initial significant land reclamation project, completed in 1922, involved the utilization of land from the dismantling of the Senate and Castle hills and included the construction of a seawall at Flamengo Beach [28]. The waterfront transformations in Rio de Janeiro were carried out according to the specifications of the renowned Brazilian artist and naturalist Burle Marx. These changes were implemented between 1930 and 1980, with the specific aim of transforming the built landscape of the city.

In 1923, the Copacabana Palace Hotel was inaugurated in the central area of Leme Copacabana beach. In contrast to the beaches at the entrance of Guanabara Bay, Copacabana exhibited distinctive geomorphological characteristics. By the 1940s, urbanization had begun along the entire beach promenade, resulting in a transformation of its landscape. The area was previously occupied by fishermen and covered by dune fields, with houses built close to the coastline. This led to damage from wave attacks during sea storms due to the narrow foredunes and sand strip. Two significant projects had a profound impact on the coastline of Copacabana: the establishment of Flamengo Park in 1965 and the artificial replenishment of Copacabana Beach between 1970 and 1972. Flamengo Park, a 1,200,000 m^2 landfill, was constructed using material from a dismantled hill. The beach nourishment project's aim was to protect buildings and the parallel Avenida Atlantica by adding approximately 5 million tons of sand, increasing the beach width from 55 m to 90 m [29]. Despite its success, the artificial nourishment did not prevent the occurrence of erosion on the western end of the beach [28]. Figure 4 illustrates the evolution of the landscape as perceived by graphic artist Carlos Gustavo Nunes Pereira, better known as GUTA.

Avenida Brasil represents a significant expressway in Rio de Janeiro, constructed in 1941 and designated as the federal highway in 1948, linking the city to Petrópolis. Spanning 58.5 km, it is the longest avenue in Brazil. At the present time, only a 2.3 km section of the avenue retains the designation "Avenida Brasil." This section is situated between Avenida João XXIII in Santa Cruz and the access point to the BR-101. Since its inauguration in the 1940s, the avenue has served as a vital transportation corridor, accommodating a diverse range of modes of travel, including trains, buses, vans, motorcycle taxis, automobiles, and trolleys. The avenue offers a contemporary driving experience and vistas of the waterfront [31]. The construction of this avenue commenced with the first built stretch, which extends in a south–north direction between the suburbs of Leopoldina, which was already in the process of consolidation at the time of construction, and Guanabara Bay (currently between the Cordovil Intersection <Av. Brasil, 640> and the Gasometro Viaduct <Av. Brasil, Caju>), works were carried out that included landfills in the sea. As documented by Abreu [32] in the early 20th century, the sparsely populated and largely undeveloped muddy coastline of Rio de Janeiro witnessed a notable surge in the formation of informal settlements. By the mid-20th century, this trend had become particularly pronounced. The Complexo da Maré was established in this area, built on landfills and mangroves, and populated by impoverished individuals attracted by local industries and accessible transportation to the city center. The low-lying coastal region is now traversed by a number of major road infrastructures, including the Gasômetro viaduct, which connects to the Rio-Niteroi bridge; the Red Line, which links the southern zone with the Rio-São Paulo highway; the Yellow Line; and the Transcarioca BRT viaduct, which crosses the suburbs to Barra da Tijuca in the western zone [33].

Figure 4. Evolution of Copacabana, by artist Carlos Gustavo Nunes Pereira—GUTA. Source: City Hall data warehouses and IPP (Pereira Passos Institute) [30].

The construction of the Urca neighborhood in the vicinity of Sugar Loaf has resulted in a notable alteration of the coastline in Rio de Janeiro. The new area was created through the process of landfill, utilizing sand from Guanabara Bay as the primary material, which was then deposited on the cliffs. The project was notable for its considerable scale, its proximity to the iconic Sugar Loaf, and for establishing a new trend of urban expansion towards the open coast to the south [34].

Human activity has significantly transformed the coastal landscape, extending changes to the islands within Guanabara Bay, particularly Governador Island. The most notable transformation was the establishment of Galeão International Airport, which was originally constructed as the Naval Aviation School on 10 May 1923. During the Second World War, the airport was transformed into a military base, with extensive upgrades to the runways, hangars, and terminals. These modifications were made in anticipation of a future transition to civilian use. By 1952, it was operating as Rio de Janeiro's primary entry port. In 1977, the airport handled all international traffic, with a new terminal opening and the old terminal remaining under military control. In 1985, São Paulo airport assumed the majority of international traffic, but Galeão regained prominence with the implementation of compulsory stopover legislation. In 1991, the airport underwent a renovation in preparation for the Earth Summit. In 1999, a second terminal was constructed, expanding the airport's capacity. Further enhancements were implemented subsequent to 2014, including the construction of a second runway, in anticipation of the 2016 Olympics [35]. Governador Island, the largest island in Guanabara Bay, has been experiencing coastal erosion issues over the past few decades. The erosion is primarily the result of the construction and assembly of seven pipelines traversing the island from the principal oil terminal on Ilha

D'Água to the Duque de Caxias Refinery (REDUC). The expansion of urban and industrial activities associated with the oil and gas industry has contributed to the exacerbation of erosion problems [36].

Paqueta Island is one of the islands that has exhibited the least change in its coastal shoreline from the colonial period to the 21st century.

Fundao Island, situated in Guanabara Bay and a constituent part of Rio de Janeiro city, Brazil, is the consequence of an artificial embankment constructed on the site of a former archipelago. The construction of this embankment commenced in the early 1950s (1949–1952) [37]. The islands that constituted the archipelago were designated Catalão, das Cabras, Fundão, Pindaí do Ferreira, Pindaí do França, Bom Jesus, and Sapucaia. The artificial embankment was constructed with the objective of providing housing for the Federal University of Rio de Janeiro (UFRJ). Figure 5 illustrates an overlay of the current island of Fundão with the archipelago prior to the inter-island fills.

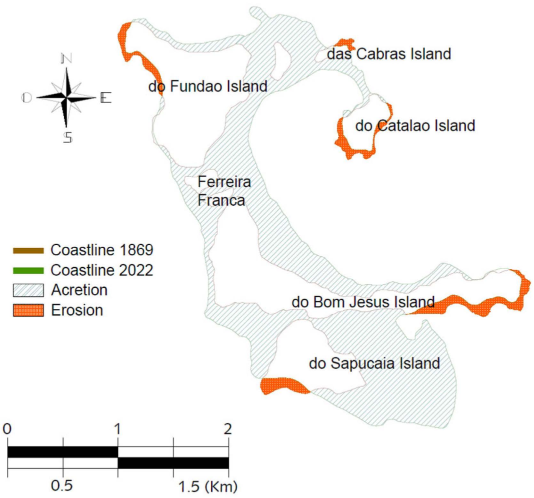

Figure 5. Superposition of the current island of Fundão with the archipelago conformed by Catalão, das Cabras, Fundão, Pindaí do Ferreira, Pindaí do França, Bom Jesus, and Sapucaia Islands, prior to the construction of the artificial barrier. Source: Own elaboration.

The interior of Guanabara Bay is home to a multitude of islands and islets, the precise number of which is difficult to ascertain. According to specialist Elmo da Silva Amador [38], the number of islands and islets in Guanabara Bay in the 16th century was 127. However, today, that number has been reduced to approximately 65. The history of the transformation and expansion of the city of Rio de Janeiro is marked by a series of landfills and other human interventions in the city's landscape. As a consequence of this process, 36 coastal islands situated in close proximity to the coastline were eliminated. The archipelagos of Ilha do Governador and Paquetá were the most resilient to the historical process due to their location. A number of other islands in the bay were also lost when they were incorporated into the mainland through the construction of artificial landfills. One such island was Ilha do Fundão, which was subsequently transformed into the Cidade Universitária following the landfill of seven other islands in the vicinity, as previously mentioned. In the present day, a significant proportion of Guanabara's islands are utilized for the purposes of naval facilities, oil terminals, and shipyards.

The urbanization of the east and southeast coasts of the state of Rio de Janeiro has been a continuous process driven by the expansion of the urban area, particularly in cities such as Niteroi, Cabo Frio, and Macaé. This expansion has been facilitated by the construction of the bridge over Guanabara Bay between Rio de Janeiro and Niteroi in 1974, oil exploration in the Campos Basin, and the growth of tourism. In light of the aforementioned considerations, the potential for the implementation of artificial beach nourishment has been proposed on several occasions, contingent upon the identification of suitable sediment sources [39]. The artificial beach nourishment has been implemented in Piratininga Beach, which serves as the starting point for the present study.

The colonial fortifications, which correspond to the constructed landscape according to this research group, were initiated in the 16th century and definitively transformed the east coastal landscape of Rio de Janeiro and Guanabara Bay. The original landscape, comprising exuberant forests, pristine waters, and small inlets, was irrevocably transformed into one of the most visited cities in the world, where the constructed, destroyed, and reconstructed landscapes coexist.

Figure 6 depicts the coastline in 1869, beginning at Cape La Gavia and continuing through Fort San Juan, where it enters Guanabara Bay, and ending at Fort Santa Cruz, the point of exit from the bay. Figure 7 corresponds with an image produced from aerial photographs obtained from Google Earth during the year 2022, which provides a more up-to-date representation of the coastline. Figure 8 illustrates the superimposition of the coastlines, depicted in varying tones and line types, to demonstrate the impact of human activities on the coastline. These activities include the construction of ports, whether for use as air or sea terminals, sports or recreational facilities, or the loss of land due to mangrove deforestation. Similarly, the principal locations that will be utilized to orient the reader are also identified.

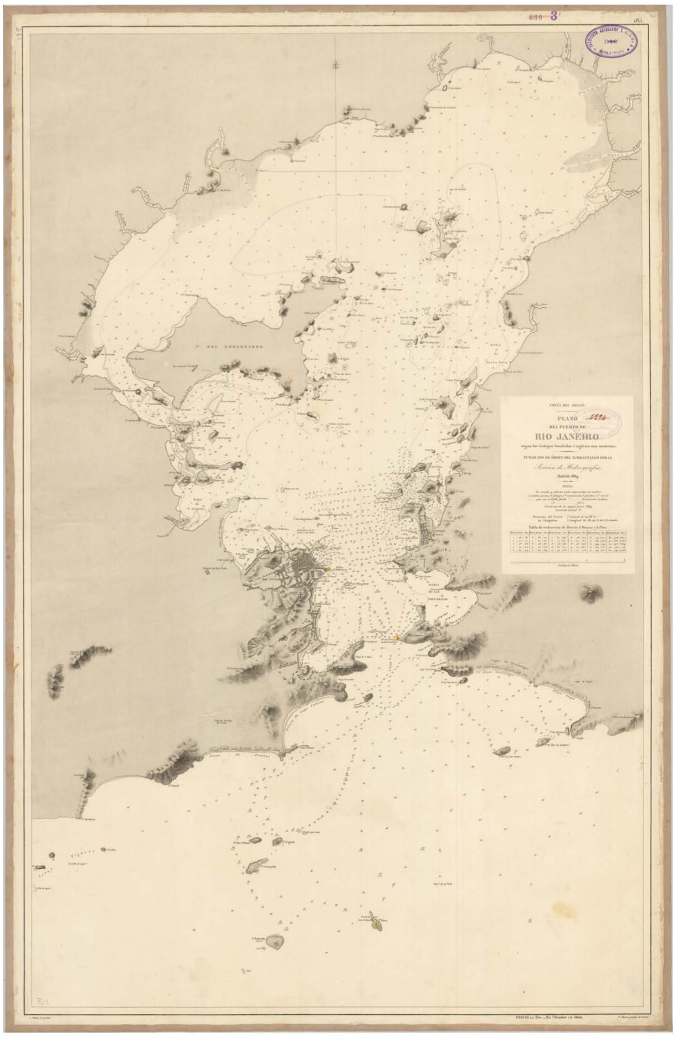

Figure 6. Map number 4294 of the Port of Rio de Janeiro, as published in the Brazilian and English works by the Hydrographic Section of the Admiralty in Madrid in 1869. Source: National Geographic Institute, Hydrographic Section, Madrid, 1869 (https://www.ign.es/web/catalogo-cartoteca/resources/html/000953.html, accessed on 4 June 2021).

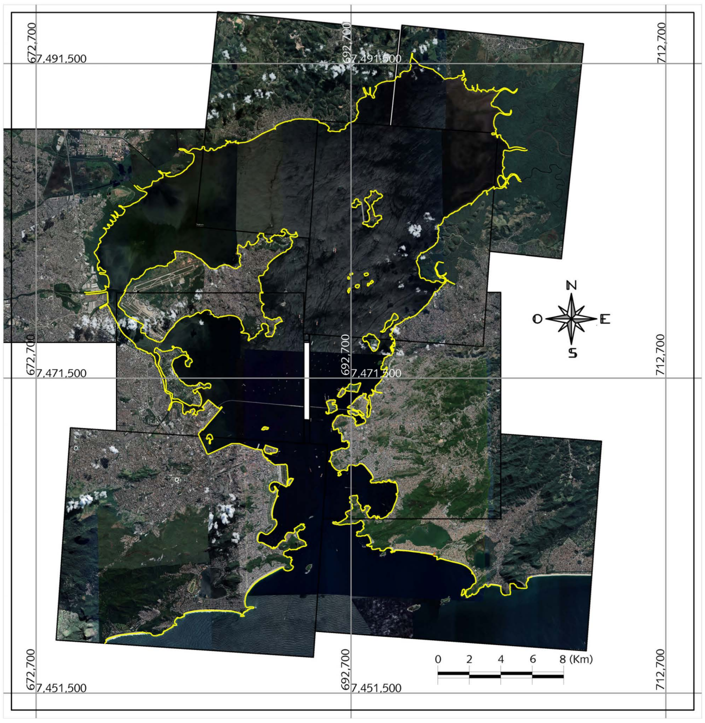

Figure 7. 2022 aerial photographs. Eight sites (framed) that correspond with the important places analyzed in this paper. Source: own elaboration, taken from Google Earth.

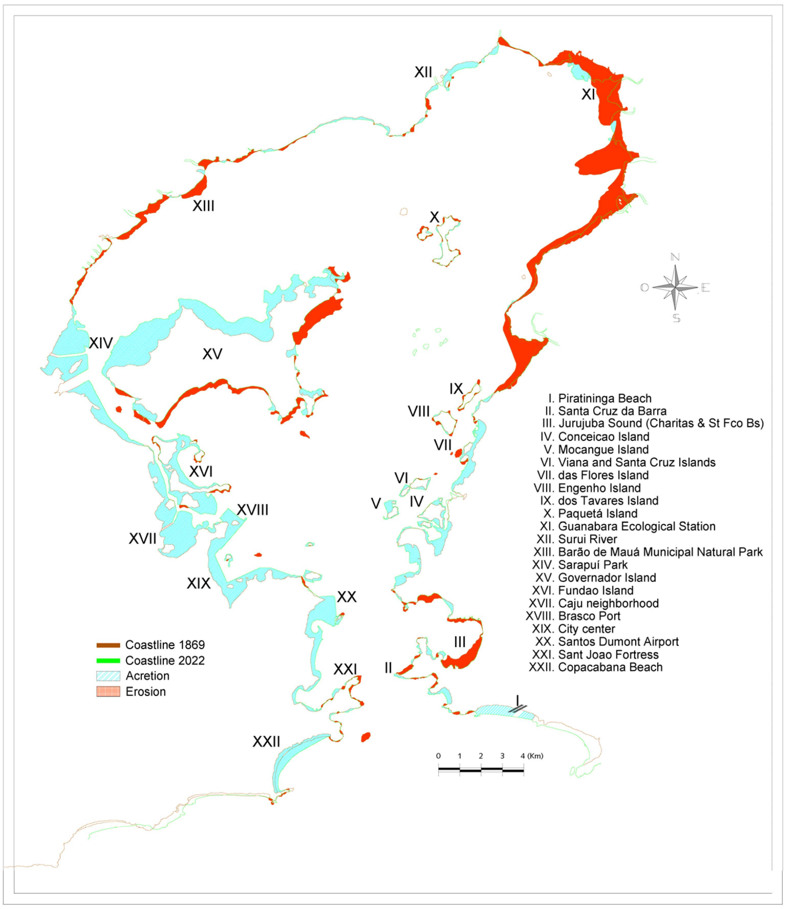

Figure 8. Coastline superimposition of the vectorized cartographic plans of 1869 and 2022. Source: own elaboration.

2. Materials and Methods

The methodology employed is identical to that utilized by this research group in their study, "Comparing the Effects of Erosion and Accretion Along the Coast of Cartagena de Indias, Colombia" [3]. The methodology requires two plans of the study area to be compared in order to show the changes to the coastline and to evaluate and quantify the area between the analyzed coastlines. For the purposes of this case study, the map in Figure 6 has been employed, which corresponds to the 4294 maps of the Port of Rio de Janeiro. This map was utilized in accordance with the Brazilian and English works published by order of the Admiralty by the Hydrographic Section in Madrid in 1869. As previously stated, the figure depicts the coastline in the year 2022.

The georeferencing of historical maps and current images was conducted using the Free Software Geographic Information System (QGis). This software accesses remote information via OGC data servers in Brazil and utilizes Brazil's official reference system, MAGNA-SIRGAS. The georeferencing employs a Transverse Mercator projection with the SAD 69/IBGE geodetic datum. The accuracy and precision of georeferencing are contingent upon the presence of control points that satisfy the following criteria: (i) The control points must be unequivocal and clearly identifiable. (ii) The control points must belong to accurately represented elements. (iii) The control points must correspond to elements that are considered to be invariable over time. (iv) The control points must have a homogeneous and uniform distribution across the study area [40].

The maps were vectorized using AutoCAD 2013, a computer-aided design software for two-dimensional drawing. A georeferenced plan was exported from QGis to AutoCAD, converting the geographic coordinates into plane coordinates. Emphasis was placed on ensuring that the vectors matched the real plan's scale accurately. The spatial objects, captured as polygonal geometries, were adjusted manually to the raster image using the zoom tool for precision. The vector precision for digitized plans is based on the minimum details of 0.2 mm $\times$ E, where E is the plan scale's denominator. The 0.2 mm constant represents the average minimum separation discernible by the human eye, resulting in a maximum real error of 0.4 m. Each vectorized coastline was assigned specific attributes for the calculations, with negative values indicating erosion and positive values indicating accretion. Upon overlaying the maps, areas exhibiting significant changes in coastline were identified. A historical analysis was conducted to observe the detailed evolution of the coastline in these areas. The extent of the coastline variations was quantified, thereby enabling the calculation of the area of change between coastlines. The estimated error was less than 5%, which is consistent with previous research conducted by the group. Table 2 shows the main anthropogenic actions on the coast of the study area.

Table 2. Chronology of anthropogenic actions on the coast.

Century	Year	Action
XVI	1502	The Portuguese arrived in Rio de Janeiro
XVI	1565	Rio de Janeiro Foundation
XVII	1612	Construction of the Santa Cruz Fort in Niterói
XIX	1808	Relocate the Portuguese court to Brazil
XIX	1814	Hotel Pharoux construction
XIX	1852	Construction of hospital and relocation of a cemetery.
XIX	1859	Gymnastics Society was established at Santa Luzia Beach
XIX	1892	Construction of the Old Tunnel
XX	1902–1906	Pereira Passos Reform
XX	1914	End of construction of the Copacabana fort
XX	1920	Development of the Copacabana neighborhood with the urbanization and construction of residential buildings
XX	1922	Construction of a seawall at Flamengo Beach
XX	1923	Inauguration of the Copacabana Palace Hotel
XX	1923	Construction of the Naval Aviation School
XX	1941	Construction of Avenida Brazil

Table 2. *Cont.*

Century	Year	Action
XX	1949–1952	Construction of Fundao Island (embankment)
XX	1952	Opening of the Santos Dumont Airport.
XX	1965	Establishment of Flamengo Park
XX	1970–1972	Replenishment of Copacabana Beach and construction of Avenida Atlantica
XX	1974	Inauguration of the Rio-Niteroi Bridge, connecting both cities through Guanabara Bay
XX	1980	Beginning of the urbanization and development of Icaraí beach in Niteroi.
XX	1992	Coastline reshaping for the Earth Summit
XXI	2000	Construction of the Niteroi Museum of Contemporary Art (MAC) on the shoreline
XXI	2000	Oil spill accident in Zone XIII Barao de Maua Municipal Natural Park (PNMBM)
XXI	2018	Construction of AquaRio in Port Zone

3. Results

Upon obtaining the base coastlines from the colonial period (1869 map) and the one obtained from Google Earth (2022), an overlay was performed. It was observed that it is not possible to make them fit as continuous lines. Therefore, the colonial coastline was left as a template, while the current coastline was moved to fit the lines more adequately and perform the analysis. Figure 8 depicts the overlap that best aligns with the two shorelines. Table 1 presents the shoreline sections that were the subject of the present study. Table 3 establishes the areas of accretion or erosion present in each section, as well as the final quantification. As observed, the study area exhibits favorable accretion, exceeding 14 km^2.

Table 3. Accretion and erosion areas in each study zone. Source: Own compilation 2022.

No.	Zone/Segment	Accretion [km^2]	Erosion [km^2]	Balance [km^2]
I.	Piratininga	1.08	0.00	1.08
	Segment between Zones I–II	0.30	−0.20	0.10
II.	Santa Cruz da Barra	0.05	−0.13	−0.08
	Segment between Zones II–III	0.21	−0.06	0.15
III.	Jurujuba Sound	0.11	−1.48	−1.37
	Segment between Zones III–IV	1.06	−0.09	0.97
IV.	Conceicao Island	0.99	0.00	0.99
V.	Mocangue Island	0.23	0.00	0.23
VI.	Viana and Santa Cruz Islands	0.17	−0.02	0.15
VII.	das Flores Island	1.09	−0.15	0.94
VIII.	Engenho Island	0.04	−0.10	−0.06
IX.	Dos Tavares Island	0.02	−0.11	−0.09
	Segment between Zones IX–X continent	0.09	−0.03	0.06
X	Paqueta Island	0.12	−0.25	−0.13
XI.	Guanabara Ecological Station	0.61	−13.52	−12.91
XII.	Surui River area	1.16	−0.55	0.61
XIII.	Barao de Maua Municipal Natural Park	0.15	−1.90	−1.75
XIV.	Sarapui Park area	5.11	0.00	5.11
XV.	Governador Island	10.79	−3.99	6.80
XVI.	Fundão Island	2.59	−0.24	2.35
XVII.	Caju neighborhood	4.01	−0.00	4.01
XVIII.	Brasco Port	1.02	0.00	1.02
XIX.	City Center continent coasline	2.52	0.00	2.52
	City Center Islands	0.25	−0.05	0.20
XX.	Santos Dumont Airport	1.26	−0.02	1.24
XXI.	Sant Joao Fortress	1.30	−0.38	0.92
XXII.	Copacabana Beach	1.47	−0.03	1.44
	Total (km^2)	37.8	−23.3	14.50

The study was conducted in a clockwise direction, commencing with Piratininga Beach and continuing through the interior of the bays, analyzing the shorelines of the main islands. The study concluded with the analysis of Copacabana Beach at the southwestern end of the bay. The following section will describe the areas in which the results were obtained with accretion or erosion values greater than 0.5 km^2.

Zone I, Piratininga Beach (Figure 9), is one of the most popular destinations in Niteroi, with an approximate length of 2.5 km. The beach is directly exposed to the Atlantic Ocean swell, and the surf is fairly consistent, although it tends to be flat during the summer months. The majority of the surf at this location originates from groundswells, with the optimal swell angle emanating from the southeast. As a consequence of the waves and the vulnerability of its beaches, over the past few decades, problems related to the destruction of the seawall and roads, among other structures, have occurred. Additionally, the variation in width along the beach arc suggests the action of the westward littoral drift current. The preponderant role of littoral drift currents in the longitudinal transport of sediments and the transverse displacement of sands from the beach face to the beach front, and vice versa, is the main mechanism responsible for the mobility of sediments along Piratininga Beach. In contrast, the results obtained in this area show a 1.08 km^2 accretion of the beach from colonial times to the present day. This can be explained by the frequent artificial nourishment of the beach as a protective measure to ensure its primary use, tourism. Given that Piratininga Beach is naturally formed by moderately selected medium sands, the artificial nourishment of this sector of the coast with borrowed sands is facilitated.

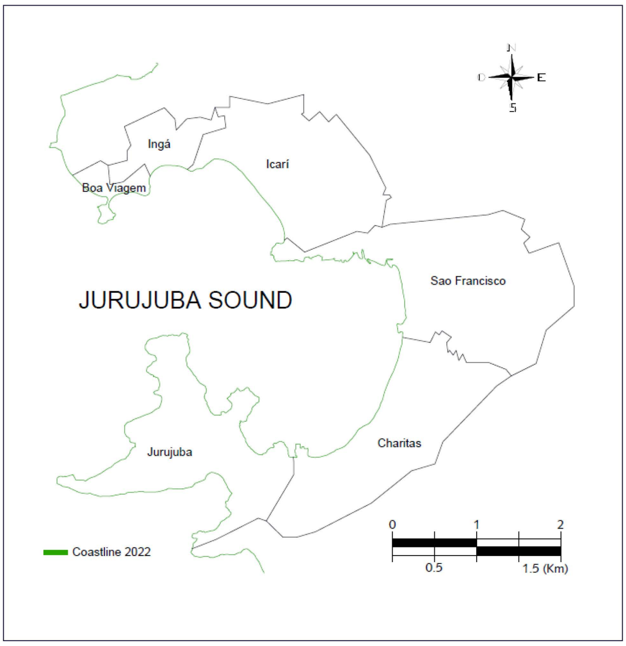

Figure 9. Bay Beaches Region (Região Praias da Baía). Source: own elaboration.

Zone III, also known as Jurujuba Sound, is part of the Região Praias da Baía. It is a small sub-bay that is sheltered by the Jurujuba promontory. The swell affecting Jurujuba Cove is primarily sourced from the south and southwest quadrants. To the north, the beaches of Boa Viagem, Flexas, and Icaraí are more dynamic, with an average wave height of 0.50 m in normal conditions and 1.5 m high in periods of swell. In contrast, the beaches of São Francisco and Charitas, located in the south, are less dynamic, with an average wave height of 0.30 m in normal conditions and between 0.50 and 0.70 m in periods of undertow. The area in question boasts a coastline length of approximately 8.000 m, with a predominant beach morphology that can be described as a ramp, exhibiting a slight slope towards the sea. This slope ranges between 11 and 14 degrees, with discrete seasonal variations that allow for the observation of small cliffs in winter, which are associated with the peaks of the beaches. To the north of the beach, there are dunes from which, on days with strong winds, sand is blown away and can reach the promenade. The sand present on Charitas Beach is characterized by its predominantly fine size (0.125 mm, between 60–80%), with a significant proportion of very fine sand (0.062 mm). Additionally, the beach is known to host the occasional occurrence of mud balls, which can be found scattered along the beach up to the area of maximum swell reach after the occurrence of undertows. The results obtained in this area indicate a net erosion of 1.37 km^2.

Zone IV–V–VI North Niteroi is situated in the interior of Guanabara Bay, where the coastline is shielded from the direct influence of the Atlantic Ocean. The results of these zones again assume accretion corresponding to 2.34 km^2 in this section, predominantly as a consequence of the formation of ports, docks, and other anthropogenic constructions. An example of anthropic action is Zone IV, Conceição Island, which was formed from the connection of two islands. Depending on the tide, these islands could be joined or separated by a navigable channel. The island is geomorphologically formed by three main hills: the first island was occupied by Morro da Fábrica, while the second island was located at Morro do MIC (formerly Wilson Sons hill) and Morro da Capela. The connection between the two islands was established when the Port of Niteroi was constructed, utilizing sand extracted from the dredging of the pier. The sandy area that was formed was definitively filled in by the neighbors themselves as construction activities were carried out. In 1958, the connection between Conceição Island and the mainland was completed. The area of V Mocanguê Island was initially formed by two adjacent islands, Mocanguê Grande and Mocanguê Pequena. The larger island was always under the jurisdiction of the Navy, while the smaller island was home to the shipyard and workshops of the Lloyd Brasileiro Shipping Company until December 1973, when it was transferred to the Brazilian Navy by the Federal Government for the establishment of the Rio de Janeiro Naval Station in July 1977. Finally, in May 1986, the channel separating the islands was filled in, the naval station was closed, and the Rio de Janeiro Naval Base was constructed.

The balance of the result of Zones VII–VIII–IX on Flores Island, Engenho Island, dos Tavares Island, and the continental section in front of the islands is accretion. However, there are small erosion sectors. The land reclaimed from the sea due to the direct action of mankind exceeds in quantitative terms, generating a positive balance that amounts to 1.49 km^2. For example, the VII das Flores Island area, which was formerly known on old maps as Marim, Mariri, and, later, Ilha de Santo Antônio and Vital, 1883, was the immigrant shelter in 1932, served as a prison for officers and soldiers arrested during the Constitutionalist Revolution, in 1968 was transferred to the Secretariat of the Navy, and since 1994 has housed the Marine base. During the 20th century, there have been continuous contributions of material that have resulted in the islands becoming integrated. Together with the other islands of the archipelago, Engenho, Ananases, and Mexingueira, the island of Carvalho forms part of the Navy base. In the mainland area, where the greatest accretion of the evaluated areas occurs, a series of landfills and expropriations were carried out in the 1980s for the construction of the Niteroi-Manilha section of the BR-101 highway.

Zone X, Paqueta Island, is situated at a greater distance from the continental zone than the other islands evaluated. It exhibits erosion and accretion zones with a negative balance of 0.13 km^2 of land loss. Areas of erosion occur on the south side where the waters become choppy in the afternoon when the southerly winds gain strength, whereas the waters at the east and west sides remain calm. The north side of the island has historically had agricultural development and shows erosion, possibly as a result of the docks on the northwestern side that intercepted sediment transport, and the salinity of the bay water in this area decreases to 9.0S in the months of higher rainfall, also causing a decrease in mangroves and estuaries.

Zones XI and XII, which include the Guanabara Ecological Station and the Surui River, exhibit small areas of accretion, with erosion being the dominant process. In this study, the area affected by erosion reached 14.07 km^2, but the final balance was negative at 12.30 km^2, indicating a loss of mangroves in the zone. However, the two zones under study are located in protected areas that have been subject to analysis with a view to preventing disasters that could cause damage to the natural environment. For example, the oil spill in the northwestern part of the bay in the year 2000 resulted in the migration of oil towards Suruí and Nova Orleans. This demonstrated that there is a possibility that other contaminants released in the same region may also be transported to these mangrove areas under certain tide conditions.

Zone XIII Barao de Maua Municipal Natural Park (PNMBM) has experienced erosion of 1.75 km^2. The PNMBM area has exhibited signs of degradation, which were exacerbated by the 2000 oil spill accident. In response, the Mangue Vivo Project was implemented, resulting in the restoration of 90 ha, which represents over 75% of the park's total area.

Zones XIV, XV, XVI, and XVII, Sarapuí Park, Governador Island, Fundão Island, and Caju neighborhood, respectively, correspond to the largest area of accretion in this study, reaching a total area of 18.27 km^2 of land reclaimed from the sea. The accretion area of these zones is the result of the dumping and landfills created for the construction of the Galeão International Airport on Governador Island, the construction of the Federal University of Rio de Janeiro on Fundão Island, and the formation and construction of the Caju neighborhood.

The study of this research concludes with an analysis of the following zones: XVIII to XXII, Brasco Port, the City Center, Santos Dumont Airport, Sant Joao Fortress, and Copacabana Beach, which are situated in the southeast part of the bay. The total accretion area of these zones is 7.34 km^2, resulting in a positive balance. Once more, the construction of fortresses, airports, and naval ports, as well as the continuous contribution of sand for the formation and maintenance of the beaches, are the primary anthropogenic factors responsible for the observed outcomes in these areas.

4. Discussion

The results were discussed in the context of previous studies conducted in the study area. Comparisons were also made with some studies that did not determine the areas of accretion and/or erosion within the coastline of the study area. However, these studies do allow for the evaluation of the dynamic behavior of the coast and its variation in terms of beach width, geomorphology, grain size, slope gradient, and other factors. Similarly, previous studies permit the corroboration of whether the location of the accretion and/or erosion areas identified in the present paper aligns with the historical development of each zone. This evidence demonstrates the impact of anthropic intervention on the coastline, providing a clear example of the coastline's variability.

The article presents a historical analysis of the evolution of the coastal landscape in response to anthropogenic influences. While the socioeconomic impact has not been considered for this case study, which limits the analysis of the consequences of coastal landscape alteration for the population surrounding the study area, this research does illustrate the historical consequences of various decisions, actions, and policies on the coastal landscape, both governmental and social. These consequences subsequently have environmental and socioeconomic implications that will continue in long-time terms.

The current configuration of Guanabara Bay is the result of the Holocene transgression, which submerged the lower reaches of the drainage network. The bay's bathymetric curves exhibit the indentations of the talvegues, which are still visible today. The bay is an area that was lowered along a fault axis that ruptured the coastal massif. The depression thus formed and opened a connection between the ocean and the Guanabara graben and served as a convergence point for the fluvial drainage network coming from the Serra do Mar escarpment and the reverse of the coastal massif [13]. The coastline is subject to change due to the influence of coastal dynamics, which, as previously stated, is contingent upon the morphology of the coastline. Figure 10, as presented by Muehe et al. [19], depicts the geomorphology of the coastline under investigation, presented in sections. This will serve as a foundation for understanding the response of each section to the behavior of the coastal climate.

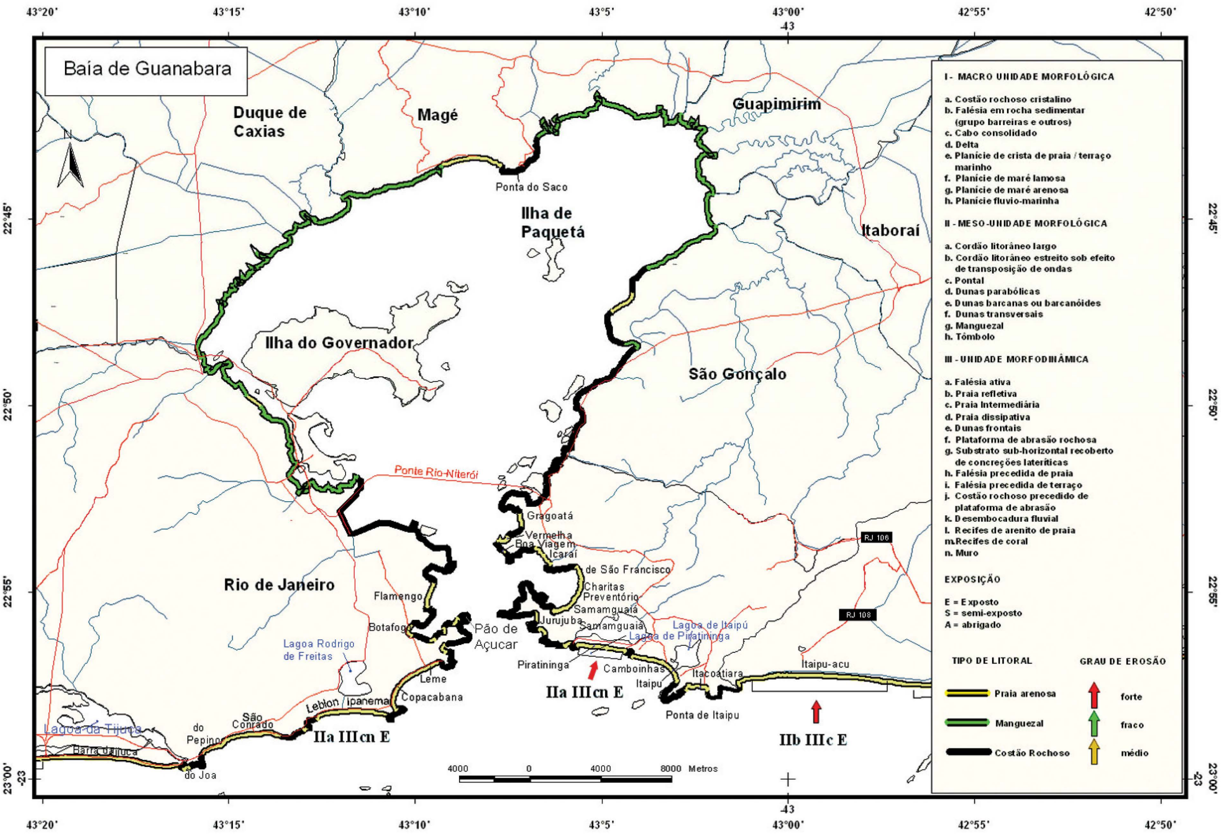

Figure 10. Coastal geomorphology of the study area. Source: Muehe, D. et al. [19].

The accretion observed in study Zone I, Piratininga Beach, with an area of 1.08 km^2, is in accordance with the recovery and anthropic protection works that are being carried out in the area, as well as the protection they have due to their location near the entrance to Guanabara Bay. The results are in agreement with those of Muehe and Lins-de-Barros [22], who posit that the beaches of this sector have undergone numerous interventions, including landfill, dredging, and the construction of seawalls, due to their location in heavily modified urban areas. In Niteroi, a seawall constructed on Piratininga Beach to protect against erosion has been repeatedly destroyed and rebuilt. Nevertheless, despite the presence of the wall, the beach profile maintains its position and sediment volume of approximately 300 m^3/m^2 (Figure 11). The findings of this research team are also consistent with the studies of André Luiz Carvalho da Silva et al. [41], who, through an analysis of the beach profile in the region over the past 30 years, have concluded that, despite the exposure of the coastline, there has been no evidence of erosion. According to Silva [42], Piratininga Beach is characterized by the predominance of waves originating from the S, with occasional exceptions where SW waves prevail, plunging waves, and spilling waves. These characteristics, as Silva continues, result in profiles with a strong angle of inclination along the beachfront, with a slight variation in the profile along the beach. Additionally, the topographic profiles reflect the performance of coastal drift currents, which influence the transport of sediments to the west during the summer. During the winter, the transport of sediments narrows at the ends of the beach arc, resulting in a reduction in the width of the beach to a maximum of ±80 m. Other studies, such as those conducted by Santos et al. in 2004 [20], Bastos in 1994 [43], and Muehe in 1975 [44], also demonstrate similar beach dynamics. The analysis conducted by Santos et al. revealed a notable variation in the average width of the beach, with a difference of 15 m between the winter and summer measurements. Additionally, the study demonstrated that rip currents play a significant role in the destruction of the seawall at Piratininga Beach, with a more pronounced impact observed at the eastern end and a gradual decline towards the western end. This observation highlights the influence of rip currents on the beach width, which is derived from sand erosion. Bastos (1994) [43] observed that Piratininga Beach exhibited a differentiated dynamic behavior along the beach. The western sector of the beach was found to be more dynamic, unstable, and vulnerable to the action of tidal waves. However, it is important to note that Bastos conducted his study during the winter, a season that may have influenced the observed results. Additionally, the beach width exhibited a variation between 17 and 55 m. Furthermore, the study revealed that the beach was undergoing an erosive process during the study period, particularly at the western end. Finally, the topographic profiles created for the center of the beach arch by Muehe in 1974 demonstrated that the beach width fluctuated between 47 and 62 m. The outcomes of the various investigations conducted from 1974 to 2005 (30 years) indicated that the beach profiles have remained unaltered, suggesting that it is possible to estimate that, if during the last 30 years, Piratininga Beach has varied between 40 and 80 m in width with a tendency towards accretion, the result obtained by this research group in the analyzed period of 150 years appears to be satisfactory.

Figure 11. Piratininga Beach. The beach still maintains its position and sediment volume. Source: Marcelo Dias (https://www.facebook.com/praiadepiratininganiteroi, accessed on 14 April 2024).

Freshwater enters the Jurujuba Sound (Zone III) through several small channels that encircle the coastline. The Cachoeira and Icaraí rivers were classified as typical urban rivers, whereas the other channels are open sewers in which liquid discharge is maintained by mixed flows of domestic effluents and rainwater. It is typical for these channels to be highly efficient at removing suspended bedload sediment during storm runoff due to their smooth and shallow concave cross profiles and steep gradients. The erosion obtained by this research group for this area, which amounts to 1.37 km^2, is in agreement with previous research carried out by J. Baptista Neto et al. [45], who also conclude that whilst impacts of modern urbanization are severe, both in terms of elevated erosion/sedimentation and associated pollutants, these are not unique, and their results also show that an earlier phase of rapid nearshore sedimentation was also identified, which appears to correlate with deforestation of the coastal margin during the early stage of European colonization. In addition to slope constraints, the processes of erosion and landslide risk in Niteroi are significantly influenced by the characteristics of the slope-forming materials. Each material has a distinct erosion pattern and varying slope failure threshold levels [46]. A slight tendency towards a decrease in the size of the Jurujuba Sound sand is observed, with the northern subzone exhibiting coarser grains in comparison to the finer sand observed at Charitas and Sant Francisco beaches. This phenomenon can be attributed to the differing levels of wave energy [47]. This trend appears to correspond to the processes observed in this area by previous research and the current results of erosion by this research group. The beaches are currently in equilibrium with the environmental dynamics of Guanabara

Bay and the prevailing sea level. The existing issues can be attributed to inadequate human intervention.

As illustrated in Figure 12, the road marked in red on the 18th-century map differs from the current topographic map in a number of ways, according to Soares da Costa [48]. The road in question (line red) connects the current neighborhoods of São Domingos and Ingá, traversing the hills between points B and E. It is also noteworthy that in the 18th century, this road connected two points on the Niteroi coast. However, with the construction of a coastal fill in the 20th century, this road no longer reaches the sea on the side of São Domingos, as can be seen in the comparison figure. In 1840, a new urban plan for the city of Niteroi was drawn up by the French military engineer Pedro Taulois (and approved the following year). This spatial configuration would only undergo a similar magnitude of change a hundred years later, during the Republican period, when the landfills (São Lourenço and Praia Grande) were built, artificially creating new land for public use [49]. The two studies—in conjunction with the historical documentation of the Conceicao, Mocangue, Viana, and Santa Cruz Islands, which have already been described in this paper—are in alignment with the findings of this research group for the Niteroi Norte zone (Zones IV–V–VI). The final balance of this zone was positive, with an accretion of 2.34 km^2. Another of the works that generated accretion of the Niteroi coastline was the construction of the Rio-Niteroi Bridge, which has 4.04 km built on the embankment (total length of 13.29 km), 50% of which corresponds to the eastern side of the bay.

Figure 12. Top—Plan of the city of Rio de Janeiro with the most essential part of its port and all the fortified places; by Jose Correa Rangel de Bulhoens, 1796. **Down**—Map of the neighborhoods of São Domingos; Boa Viagem and Ingá, 2022. Source: map from the National Digital Library [cart209337] (2022) and ESRI map (2022).

The beaches in the municipality of São Gonçalo (in Zones VII–VIII–IX) are among the most severely degraded and poorly characterized of Guanabara Bay. Beira Beach, situated on the island of Itaoca, measures 330 m in length and 19 m in width. A pier was constructed on the northern boundary to support the state's oil industry, and the beach exhibits clear signs of degradation and morphological changes that are evident due to the activities conducted along this coastline. The 11 m section of the beach (with a 15° slope) exhibits a less degraded appearance due to the tidal fluctuations, which move trash to other areas. The quartz sands at Beira Beach exhibit a gradational distribution, with medium-grained sand comprising 48% and very coarse sand comprising 41%. The proportion of coarse sand is also elevated at the beachfront, accompanied by a notable accumulation of gravel. This is in contrast to the low energy of this stretch of the sheltered coast of Guanabara Bay. The results of the analyses conducted by Silva et al. [49] indicate the presence of a bimodal sedimentary pattern, which is also observed in Praia da Luz. This pattern, as previously noted by Amador [14], is characteristic of some low-energy beaches in Guanabara Bay. As previously stated by the aforementioned author, the origin of these sediments is attributed to the contribution of the local geology, specifically the Caceribu Formation. The length of Praia da Luz beach is 1084 m, oriented southwest–northeast. The northeastern edge of the beach is notable for its abundance of mangrove vegetation. The Praia da Luz beach has a narrow ramp profile, with a width of only 13 m and an inclination of 12° with respect to the waterline. The sediments of this beach are predominantly composed of medium- to coarse-grained quartz sands, with gravels comprising 12% of the total. During the spring low tide, the intertidal zone of the beach reveals a muddy substrate with a considerable accumulation of waste. The notable presence of mud is a consequence of the proximity to the mangrove [18]. The characteristics of the beaches in this area are in precise alignment with the results of the coastal accretion obtained in this paper. Therefore, they can be considered in accordance with the geomorphology of the coastline obtained in previous studies, as well as with the contribution of material generated for the connection of the Engenho and Carvalho islands for the construction of the Marine Base and the landfills required for the construction of the BR-101 highway in the Niteroi-Manilha section.

The quantitative analysis of the northeastern portion of Guanabara Bay (Zones XI–XII), as presented by Fernandes et al. [50], indicates significant modifications in the surrounding area within the Guapimirim Environmental Protection Area. The analysis was divided into four periods: Between 1938 and 1974, the coastline exhibited a loss of 1.44 km^2 of water surface. Such evidence can be associated with the aggradation of the region, which occurred as a result of deforestation to provide resources in accordance with the economic models that were in place during the period under analysis [14]. In the second period of the 1974–1984 study conducted by Fernandes et al., a total of 0.65 km^2 was subtracted from the designated protection area. However, in the third and fourth periods, the changes in coastline are not discernible on the scale utilized for the research [50], which may indicate a reduction in the impacts resulting from the pressure of human activities on the water body [51]. According to Moraes et al. [52], the natural recuperation of mangrove ecosystems located within the limits of the Guapi River can be associated with a wider control of human actions due to the monitoring policies established. One illustrative example of such a movement is the enactment of Decree No. 90.225 on 25 September 1984, which established the Guapimirim Environmental Protection Area and the protection of its mangrove areas.

The deforestation, rectifying, and channeling of some rivers that drain into the bay, changing their course and flow rate [53], have influenced the deposition of sedimentation around the basin of Guanabara Bay [54]. It can be observed that mangroves, which previously served as effective filters in areas between tides, have been largely depleted in areas where they were once abundant [14]. The complete modification of the northeastern portion, according to Fernandes et al. [50], was approximately 2.09 square kilometers. The erosion area obtained by Fernandes et al. is considerably lower than the results of this paper. Nevertheless, it is evident that the discrepancy can be attributed to the shorter duration of the study, given that this investigation encompasses nearly a century more of cartographic analysis. Another crucial factor to be taken into account is the type of vegetation present in these areas. This corresponds to mangroves that have been directly affected by contamination and misuse by humans. Figure 13 illustrates the extent of Zones XI–XII.

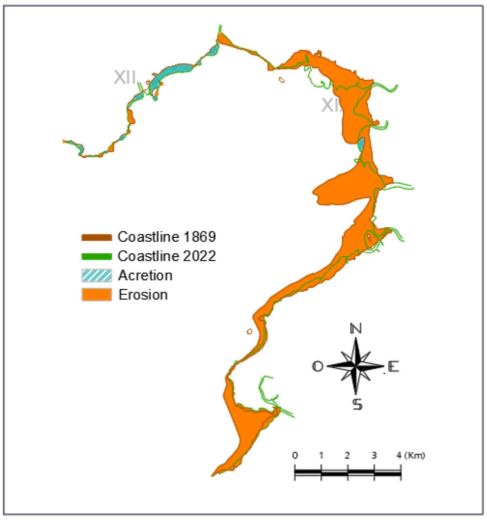

Figure 13. Zone XI and XII. Erosion and accretion areas and Manguezal do Mangroves of the Reconcavo of Guanabara Bay and APA Guapimirim Source: own elaboration and Ricardo Gomes/Instituto Mar Urbano (https://institutomarurbano.com.br/projeto-guanabara-verde/, accessed on 22 May 2024).

The mouth of the Iguaçu River (Zone XIII) is included in Guanabara Bay depollution plan, which is funded by the World Bank and managed by the Rio de Janeiro state government. The project entails dredging operations with the objective of enhancing water circulation and facilitating the removal of contaminated sediments from the riverbed. Notable features in this region include the Petrobras Duque de Caxias refinery and petrochemical facilities on the left bank, and the Gramacho landfill, the largest urban waste landfill in Rio de Janeiro, on the right bank. Furthermore, the majority of the rivers that flow into the bay are severely degraded [55]. With respect to the northwestern part of the bay, the low surface oxygen content in the Iguaçu River is related to existing discharges of pollutants. In summer, the bottom oxygen levels in the central and northeastern bay stations were extremely low (between 0.12 and 0.3), indicating the presence of an anoxic zone in this region [56]. Previous research has consistently demonstrated that anthropogenic activities are responsible for the erosion observed in Zone XIII of this study.

With regard to the zones from XIV to XVI, the multi-temporal analysis of the northwestern section of Guanabara Bay by Fernandes et al. [50] indicates the movement of the coastline towards the shore, resulting in the addition of areas by landing, the disappearance of Maria Angú Beach, and the incorporation of Ferreiros Island to the continent between 1938 and 1974. Additionally, between the years 1974 and 1984, a crescent-shaped movement of the coastal area occurred in the segment that begins at the base of the Rio-Niteroi Bridge and extends southwestward toward Fundão Island. The area—previously inundated and comprising tidal plains—was reclaimed, with the island of Pinheiro becoming an integral part of the mainland. From 1984 to 1997, the coastal area continued to undergo changes due to urbanization. The successive landings on the northern area of the Meriti River established a new contour of the coastline. The elevated rates of sedimentation and aggradation observed in the deforested channel between Governador Island and the continent resulted in a loss of water surface. Following the 1970s, the continued use of the landings for large engineering projects was facilitated by the economic model in place at the time [14]. The analysis of [50] also indicates that there were few discernible changes in scale between 1997 and 2015 when compared to previous periods. The Fundão Channel is also included in the PDBG, and the actions taken for this project demonstrate that the present dynamics of the evolution of Fundão Island (Zone XVI) indicate a recuperation of the environmental reservation area, a decrease in the use of grass, and an increase in the constructed area in some portions of the island. Furthermore, this study examined the impact of the construction of the International Airport on the geomorphology of Governador Island (Figure 14). As a result of this construction, the island (Zone XI) underwent significant changes in its contour, with the addition of new areas and a larger perimeter at the northwestern side. The changes in the northwestern region (Zones XIII to XVI), as delineated by Fernandes et al. [50], covered an area of approximately 14.78 km^2, which is consistent with the area of 18.27 km^2 obtained in this research, which considers approximately 100 more years of evaluation.

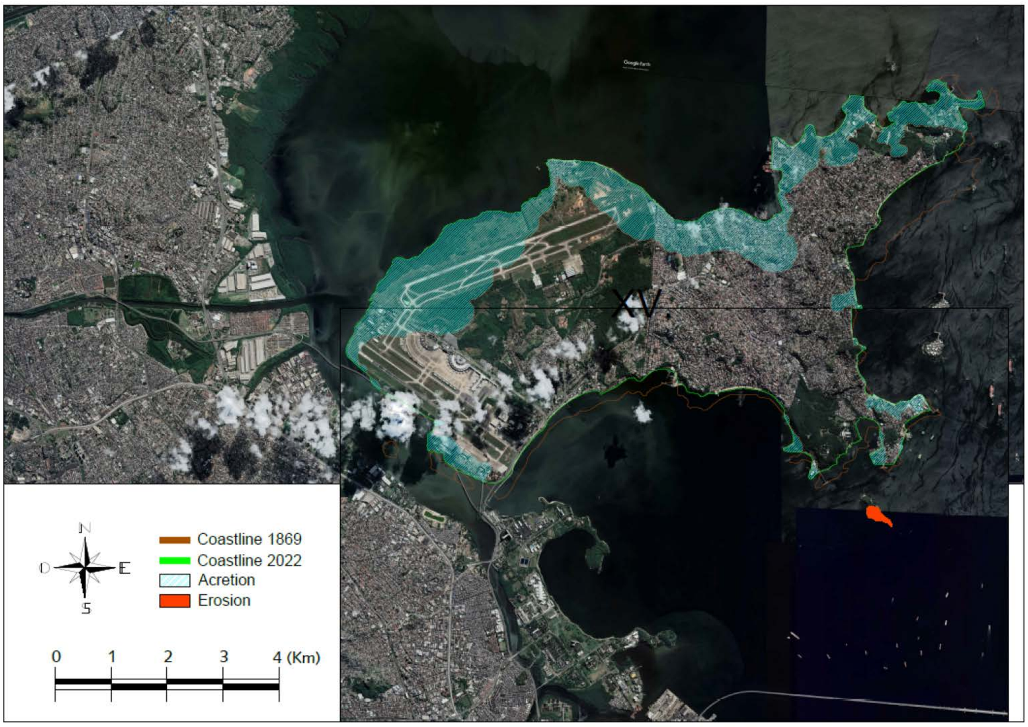

Figure 14. Accretion and erosion in Governador Island (Zone XV). Source: own elaboration, taken from Google Earth.

The coastline of the zones from XVII to XXI (Figure 15), situated between the present city center and the Botafogo embayment, including the Caju neighborhood, underwent significant alterations at the beginning of the 20th century. Some of the beaches were lost due to land reclamation, while others underwent extensive modifications to their contours. Sea storms and damages observed on some beaches, such as Saúde [25,26] and at the shore of Glória beach, encouraged work on the coastline [28]. The actions of other entities contribute to the accretion areas in the zones, including Flamengo Park. This Park was constructed on land reclaimed from the sea and consists of a network of public spaces extending along the coast of Guanabara Bay, from Santos Dumont Airport to Botafogo Bay (1.3 km^2). This built edge is separated from the city by an expressway for road traffic, acoustically isolated by elevations of the land itself. Additionally, the Museum of Contemporary Art of São Paulo was constructed on a plot of land measuring 0.4 km^2 that was granted in 1951. This plot is located in the Flamengo atrium, adjacent to Beira Mar Avenue, in the center of the city. In order to facilitate the construction of the museum and its adjoining spaces, the hill in the vicinity was also excavated [57]. The accretion area determined by Lins-de-Barros et al. [28] was calculated and compared with the results of Rey [57] and with the findings of this research. It was found that there was agreement between the three values.

Copacabana Beach (Zone XXII) presents accretion that has been derived from a variety of sources, including the continual influx of materials that have been received over time. For instance, during the Pereira Passos administration, a strip of land reclaimed from the sea was obtained for the construction of Avenida Atlantica, which measures 4.5 km in length and is situated between the Leme and Copacabana forts. This resulted in the avenue increasing from two to eight lanes, the addition of three new sidewalks (28, 14, and 10 m wide), and Copacabana Beach reaching a width of 80 m [57]. The accretion area resulting from Rey's data provides further corroboration that the results of the present study accurately reflect the behavior of shoreline change in this zone.

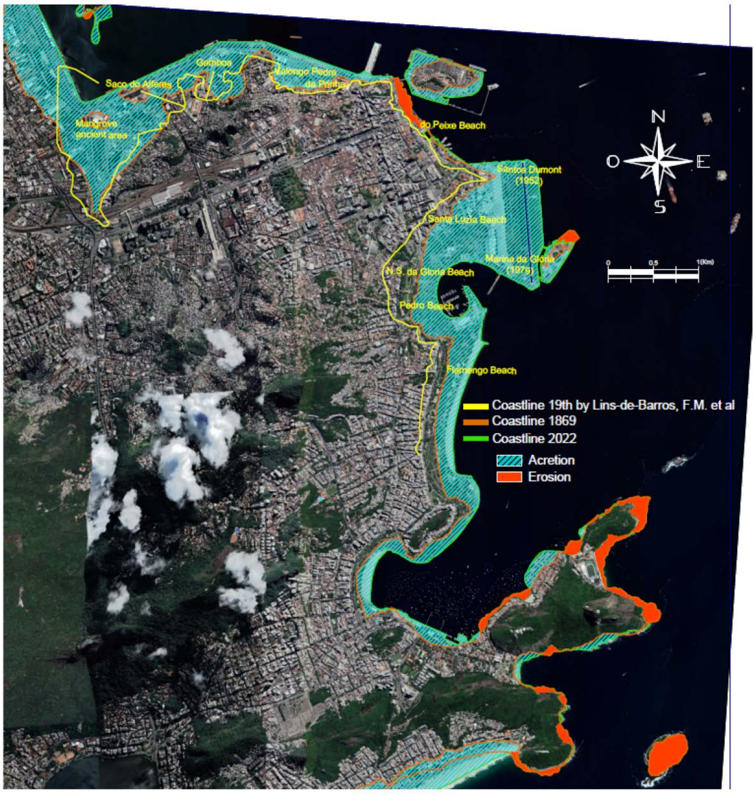

Figure 15. Zones from XIX to XXI, drawn from a city plan from 1867 and bibliographic sources over a recent satellite image from Google Earth in 2022. Source: Lins-de-Barros, F.M. et al. [28] and own elaboration.

It is anticipated that for Zone XI (PNMBM—Guapimirim EPA), mangroves will undergo notable alterations as a consequence of the sea level rise. This may culminate in a phenomenon known as "mangrove squeeze," whereby the vast majority of the mangrove ecosystem becomes perpetually inundated. In the urban centers of Rio de Janeiro (Zones XV to XXI) and Niteroi (Zone III), the sandy beaches of Copacabana (Zone XXII) and Ipanema will narrow and are unable to retreat due to the high level of urbanization in the area. Furthermore, the surface area of the Rodrigo de Freitas and Piratininga lagoons will increase. It is anticipated that coastal flooding will become more prolonged and extensive [58]. When considered alongside other factors, such as alterations in wave formation and river runoff, these consequences will serve to compound the difficulties currently faced by the inhabitants of Rio de Janeiro.

5. Conclusions

The eastern coast of Rio de Janeiro and the coastline of Guanabara Bay exhibit a clear correlation with the landscape concepts delineated in this research. The original landscape represents the landscape that existed in the bay prior to the arrival of the Portuguese on the continent. During the colonial period, the constructed landscape was produced, during which the population's constructions were in harmony with the natural spaces. The destructed landscape is the consequence of anthropogenic interactions that have occurred over the past century. These interactions have been further compounded by the accumulation of pollution and the construction of buildings along the coastline. The concept of the reconstructed landscape may be considered reflected in the work of Burle Marx, who attempts to restore the harmony of the coastline through interwoven elements.

The interior of Guanabara Bay is protected from the effects of storms, primarily due to the presence of storm waves from the southeast that are intermittently felt in the Flamengo and Botafogo inlets and along the edges of the beaches of Niteroi. On Governador Island, the combined effect of waves generated by the northeast wind and the accumulation of water can result in flooding of the beach. However, in general terms, the changes to the coastline in the study area are largely the result of anthropogenic activities that have been conducted since the colonial period.

The anthropogenic activities have undergone significant alterations in the bay due to the accumulation of pollutants, which has resulted in the loss of mangrove areas, the construction of landfills, ports, and airports, the addition of sand to the beaches, and other human-made structures that have reclaimed land from the sea. Furthermore, such structures have facilitated the integration of beaches with the mainland.

A comparison between the western and eastern portions of the bay reveals that the greatest accretion to the coastline occurred in the western part of Rio de Janeiro city. The utilization of Guanabara Bay for industrial, oil, petrochemical, and naval purposes, in conjunction with investments in ports and shipyards, transformed the Rio de Janeiro east coastline into the most significant and most affected region of Brazil. Nevertheless, the detection and registration of modifications to coastlines also include areas that have been lost, particularly in the north (Zones XI, XII, and XIII), where a significant portion of mangroves have been affected, either by destruction or by pollution emanating from the rivers draining the Baixada Fluminense. The eastern side of the bay is characterized by the presence of artificial shorelines in Niteroi and Sao Gonzalo.

The east coast of Rio de Janeiro and the coasts of Guanabara Bay show a positive balance of 14.5 km^2 (+37.8; −23.3) as a result of artificial landfills for the construction of ports and airports or beaches that need a constant supply of sand to maintain their main use, tourism. However, we should not forget the importance of the area lost during the period studied, which is 23.3 km^2 and corresponds to the area affected by the loss of mangroves. Fortunately, in recent years, projects have been implemented to protect these areas.

This research, as a case study of a general research project on the evolution of coastal landscapes in several port cities of the American continent, demonstrates the considerable impact of human activities on the changes occurring along the coastline and the coastal landscape. It also highlights the necessity of implementing measures to mitigate coastal erosion and prevent damage associated with environmental, social, and economic losses. This research serves as a call to action for political and societal entities to engage in active participation in the aforementioned processes.

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