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Impacts of Climate Changes on Management Policy of the Harbors, Land Areas and Wetlands in the São Paulo State Coastline (Brazil)

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Abstract

Santosharbor and São Sebastião Oil Maritime Terminal are the most important oil and gas facility in the São Paulo State Coastline. Santosharbor had, in the last decade, increased rapidly the container handling rate, being the first in Latin America. Santos Metropolitan Region is one of the most important of Brazilian Coastline, also considering the tourism. For that great economic growth scenario it is very important to have wave climate and tidal levels well known considering the sea hazards influence in ship operations.

Since the hind-cast just represents the deep water wave climate, to make time-series of the wave's parameters in coastal waters, for evaluation of sea hazards and ship operations, it is necessary to take into account the variations of those parameters in shallow waters with coastal instrumental data. Analysis of long term wave data-base (1957-2002) generated by a comparison between wave's data modeled by a "deep water model" (ERA40-ECMWF) and measured wave's data in the years 1982-1984 by a coastal buoy in Santos littoral (São Paulo State, Brazil) was made. Validation checking procedures with instrumental measurements of storm surges made in other years than 1982-1984 shows high level of confidence.

These data, obtained from the climatological analysis compared with a data set found from a scale model of the whole area of Santos Bay, Estuary and nearby beaches (Brazil), showed the impact of maritime climate changes, wave climate and tides upon harbor and coastal structures maintenance, beaches stability, tidal inlet saline intrusion and wetlands flooding.

In the same time, the complex environmental system, that characterized the area included between Santos and Caraguatatuba, generates different natural hazard event affecting the maritime activity. A comparative study about the coastal flooding (Santos area) and the fluvial flooding (Juqueriquerê river) was conducted. An analysis about the sea level rise, the wave climate and the flooding risk as well as the sediment transport was developed.

Considering the increasing of the sea hazards, the high values of the facilities and infrastructures in São Paulo State Coastline, it is necessary to mitigate the risks from the point of view of the harbor and coastal structures maintenance and projects purposes increasing defenses procedures. Hence, based on the results obtained by the Authors in previous researches, are highlighted guidelines strategies suggested for Access Channels dimensions, wharves free-board, jetties and breakwaters dimensions, dredging rates, rigid and flexible littoral defenses, saline intrusion and land protection against flooding (including wetlands).

Keywords: Climate change; Geomorphology; Risk assessment; Harbor operations, Waves; Maintenance policy

Introduction

As well know the climate change affect the human activity, the agriculture and the industry [1] as well as the tourism business [2]. However a less bibliography was developed on the effect of the climate change on the maritime navigation. In fact, also if some studies were conducted about the effect of the climate change on the wind conditions and the wave action, the studies about the management and the policies are focused principally about the mitigation of the greenhouse gas emissions (GHG) generate by the navigation [3,4].

Nevertheless it is evident an inadequate bibliography about the effect of the climate change on the maritime navigation. For this reason a less literature is present about the management policy that the Government and the Organizations responsible for the port control can apply to sustain the shipping business due to the climate change effects.

There is the awareness that conditions of bathymetry, tides, winds, currents and waves for next decades shall have climate changes impacts on maritime navigation. The risk is understood, but only in a qualitative way, as composed by Hazard, Exposure and Vulnerability [5].

This paper goal is to overcome the contraposition that it emerges between the defence against the hydraulic risk and the management to preserve the environmental protection for nautical purposes. Moreover, basing on the results obtained by the Authors in the previous published researches, the highlighted guidelines strategies are suggested for access channels dimensions, wharves free-board, jetties and breakwaters dimensions, dredging rates, rigid and flexible littoral defenses, saline intrusion and land protection against flooding (including wetlands).

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Material and Methods

The IPCC and PIANC recommendations [4], about the study of the impact on the climate change on the maritime navigation, are to focus on the met ocean variables such as wind, waves, sea level and ice.

Although large-scale climatic processes are driven by the ocean-atmosphere exchange system, very few studies are available on maritime impacts compared to continental impacts due to shorter data series and fewer human consequences [4].

Some analysis about the increasing of the sea level was conducted by Bindoff et al. [9]. The Authors indicates that the global mean sea level increased at an average rate of about 1.7 ± 0.5 mm/year during the twentieth century and that the rate has been slightly higher over the period 1961 to 2003.

In other the climate model prediction elaborated by the IPCC panel [10] shows that the global average rate of rise over the twenty first century will be 25 mm/year, implying that mean sea level will be 0.2 ÷ 0.5 m higher in the 2100 than 2000.

In the same time the waves conditions could be affected by climate changes in a number of aspect. Threnberth et al. [11] reports a statistically significant trend of increasing annual mean and winter mean significant wave height (H_s) for the mid-latitude North Atlantic and North Pacific, western subtropical South Atlantic, eastern equatorial Indian Ocean, and the East China and South China Seas. It also reports statistically significant decreases in H_s for western Pacific tropics, the Tasman Sea and the south Indian Ocean. Similar trends are found for the 99% extreme H_s with a maximum increase of winter extreme H_s of 0.4 m per decade in the North Atlantic. The worsening of wave conditions in the north-eastern North Atlantic is most likely connected to a northward displacement of the storm tracks, with decreasing wave heights in the southern North Atlantic [12].

Following these indications, it is possible to understand how the regional analysis of the sea level and the wave climate become important as shows by Debernard and Roed [13] and by Sterl et al. [14].

Considering the lack of bibliography and researches developed in this topic in the South Atlantic and in particular along the coastal line of the South of the Brazil, it was activated in 2010 a joint project called "Rede Litoral" (<http://www.redelitoral.ita.br/>). The Research Unit, based in the São Paulo University – Polytechnic Institute, has the goal of the research focused on the study of wave and tidal level analysis, maritime climate change, navigation's strategy and impact on the coastal defenses along the São Paulo Coastline Harbor Areas (Brazil).

As well indicated in the Introduction, this paper summarizes the research developed by the Research Unit of the São Paulo University [6-8,15-17] concentrating on the management policies.

This study was developed analyzing three different aspects of the problems (sea level, wave climate and sediments transport), apparently distant from each other, but, in fact, coordinated as well shows by the PIANC report [4].

The long term tidal level variability (high tide, mean sea level and low tide) assessment considering the Santos Dock Company (CDS) tidal variability (Highest High Water, Mean Sea Level and Lowest Low Water) for the last six decades, comprising three moon nodal cycles (58 years) shows a consistent response of relative sea level rise. Those figures were of similar magnitude than the other long term tidal series recorded in São Paulo Coastline, at the tidal gauges of Cananea (1955-

1992), according to Franco et al [18], 200 km southward, and Ubatuba (1954-2003), 200 km northward (Figure 1).

Then a scale model of the Santos Bay, estuary with the Santos Harbor (Figure 5) was used to evaluate beach erosion and the land and mangrove wetlands flooding (Figure 6). This model was used to modeling tidal cycles and wave climate in the area nearby beaches of Santos [16]. The sea level data obtained by the simulation with the physic model were used to validate the measured data in the hydrometer of Santos Harbor. The high confidence obtained by this comparison, confirmed the validity of the long term data base used for the analysis of the sea level rise.

Considering the problem generated by the short time that the wave data are recorded by the buoy, an innovative methodology is developed in this research.

A long term wave data-base (1957-2002) was made by a comparison between wave's data modeled by the European deep water data base meteorological model ERA-40 Project [19] and measured wave's data in the years 1982-1984 by a coastal buoy in Santos littoral (São Paulo State,

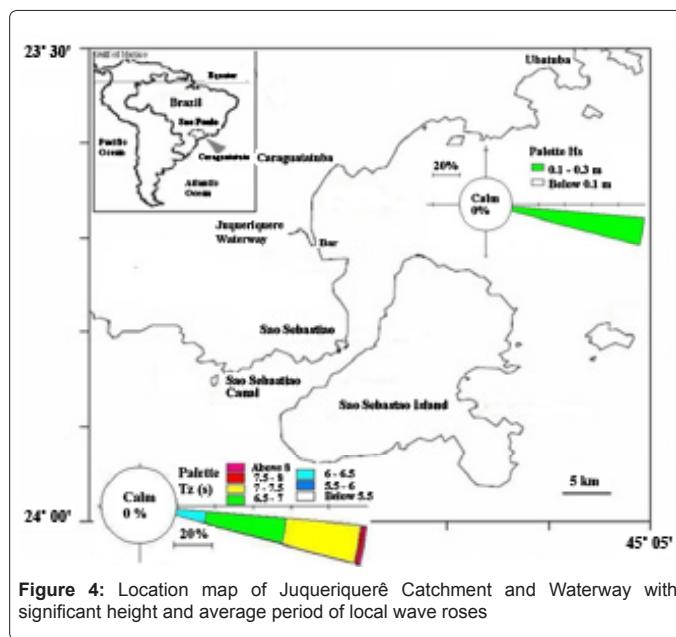
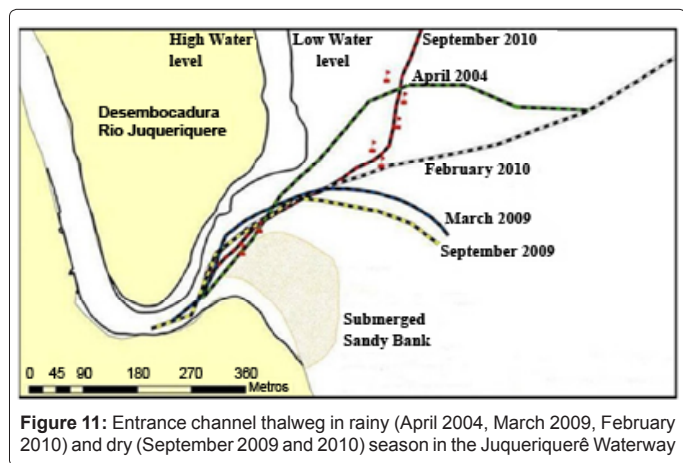
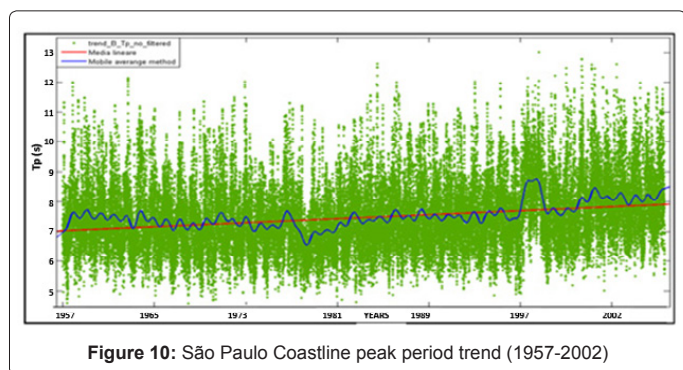
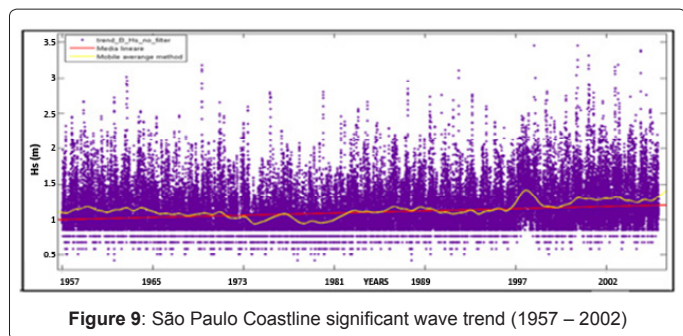


Figure 4: Location map of Juqueriquerê Catchment and Waterway with significant height and average period of local wave roses



Figure 5: Aerial view of Santos Bay, Estuary and Harbor



scenario, or an increasing in the damage rate and maintenance costs of those existing structures.

Finally, referring to [6] for what to concern the study and the results about the Juqueriquerê Catchment, it can be summarized that:

- The increasing of the sea level rise is included between 50 to 100 cm/century in the next decades in agreement with the IPCC scenario [10]
- The increasing of the sea level rise generates a flooding of around 50% of the Santos Estuary mangroves and around 100m of the beaches as well demonstrate by the simulation of the physical model
- The climate change impacts on the increasing of the H_s for a 0.4m in the next 50 years as well as in the peak period of the wave
- These calculated increasing of the significant wave height and

of the peak period are in agreement with the wave climate obtained by the measured data for the Juqueriquerê Catchment and Waterway

- In the Juqueriquerê Catchment and Waterway, the composite effect of the increasing of the significant height of the wave with the increasing of the storm and the associated flooding, generates the channel thalweg (Figure 11)
- The increasing of the significant wave height generates a possible increasing of 200% per century for the new design scenario in the harbor's structures

This analysis confirmed how the system is to be considered as a complex system where the effects on the channel, breakwater and harbor structures are generated by sea level rise, the wave climate and the flooding jointly with the sediment transport.

The consequences for navigation purposes, considering depths and channel widths are very complex and are summarized in Figure 12 elaborated considering the obtained results and the related assumptions.

As an example of some possible structural solution, it can be referred at the cost-benefit structural solution to reduce dredging costs in the Santos Access Channel proposed by Arasaki and Alfredini [20] and by Alfredini et al. [21]. The Authors proposed a solution with jetties in the Santos Access Channel which will reduce present maintenance dredging rates and will produce beach enlargement (Figure 13).

Conclusions

The paper summarizes ten years of research about the impact of maritime climate changes in the São Paulo State Coastline, developed by the Authors mainly in the Santos area, where there is the major amount of hydrodynamics data. It was possible to reach the goal of quantifying the magnitude order of tides and wave changes and to correlate them with the impact on maritime structures and the proposed mitigatory measures and structures.

Based on the quantitative assessment made it is possible to present the following and innovative strategic plan and the maintenance policy focusing on the navigation and coastal defenses for São Paulo State Coastline:

| | |
|---------------------------------|--|
| 1. Protection | <ul style="list-style-type: none"> • Wetlands restoration • Shoreline enhancement and land preservation • Jetties, seawalls, dikes construction/ upgrades against higher design waves and to 1 m of relative sea level rise |
| 2. Resistance and Resiliency | <ul style="list-style-type: none"> • Life cycle upgrades: 1 m higher elevation of quays • Increasing the external access channel width • Increasing maintenance dredging and capital dredging to enlarge external channels and for milder bank slopes |
| 3. System Management | <ul style="list-style-type: none"> • Focus investments on lower-risk assets and shift operations away from higher risk assets |
| 4. Impact Management | <ul style="list-style-type: none"> • "Green Port" to manage emissions and other impacts |
| 5. Information and Coordination | <ul style="list-style-type: none"> • Develop information to support consistent risk assessment, best practice responses, and necessary partnerships between ports and their host regions |

Considering the awareness about the importance of climate changes impacts in a coastal area prone to extreme flood and erosion events,

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