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Departamento de Física

Dulce Maria Chuvas Gordinho Maia Fradinho

Evolução da Maré na Ria de Aveiro: Componentes Astronómica e Meteorológica.

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Ciências do Mar e da Atmosfera, realizada sob a orientação científica do Professor Doutor João Miguel Sequeira Silva Dias, Professor Auxiliar com Agregação do Departamento de Física da Universidade de Aveiro.

O Júri

Presidente	**Professor Doutor José Manuel Henriques Castanheira** Professor Auxiliar do Departamento de Física da Universidade de Aveiro
Arguente	**Doutora Ana Teresa Picado** Investigadora Auxiliar do Centro Interdisciplinar de Investigação Marinha e Ambiental da Universidade do Porto
Orientador	**Professor Doutor João Miguel Sequeira Silva Dias** Professor Auxiliar com Agregação do Departamento de Física da Universidade de Aveiro

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Palavras-chave Análise Harmónica, Propagação da Maré, Maré Astronómica, Maré Meteorológica, Ria de Aveiro.

Resumo A Ria de Aveiro é um sistema lagunar pouco profundo situado na costa noroeste portuguesa, separado do mar por uma ilha barreira e está ligado ao mar por um canal fixado pelos molhes Norte e Sul. Neste trabalho pretende-se estudar as alterações das marés induzidas por modificações geomorfológicas entre 1987/88 a 2017, verificando as alterações na amplitude e fase dos constituintes de maré: $M_2, S_2,\ M_4, M_6$ e MSf, durante esse intervalo de tempo. Este trabalho também visa a determinação da frequência das sobre-elevações da maré de origem meteorológica na Ria de Aveiro, entre 2012 e 2017, determinando quais os fatores que mais as influenciam - variação na pressão atmosférica, intensidade e direção do vento e precipitação. Os dados utilizados neste trabalho foram recolhidos por marégrafos localizados nos principais canais da laguna. Foram elaborados gráficos de variação anual da amplitude e da fase dos constituintes de maré: $M_2, S_2,\ M_4, M_6$ e MSf (determinados por análise harmónica usando a aplicação T-Tide do Matlab), para estudar a sua evolução entre 1987/88 e 2017, permitindo assim, verificar a existência de alterações relevantes ao longo do tempo. Séries anuais da maré meteorológica foram determinadas para cada ano entre o período de 2012 a 2017, subtraindo ao nível da água medido nos marégrafos a previsão da maré astronómica, para se fazer o estudo da distribuição das anomalias positivas e negativas em cada estação estudada, e compreendendo a relação entre as variáveis meteorológicas e a formação da sobre-elevação das marés. Com esta finalidade, foram elaborados gráficos da pressão atmosférica, intensidade e direção do vento, precipitação, o nível da água medido e com as residuais. A partir dos resultados obtidos, verifica-se que, para cada estação, de uma forma geral, os valores anuais de amplitude dos constituintes estudados, estão a aumentar enquanto a fase está a diminuir. Entre 1987/88 e 2002/03 houve um aumento de amplitude nas estações estudadas, sendo esta mudança uma consequência do aumento da profundidade dos canais de navegação devido às operações de dragagem realizadas em 1998. De 2012 a 2017, e após o aumento do molhe Norte, os valores anuais permitem concluir que não há variações significativas na amplitude ou fase. Assim, o aumento do molhe Norte não produziu mudanças significativas na dinâmica da maré na Ria de Aveiro. Através da análise da maré meteorológica, verificou-se que as anomalias positivas são mais frequentes do que anomalias negativas. Dos diferentes eventos ocorridos entre 2012 e 2017, apenas dois influenciaram toda a laguna, tendo sido determinados pelas condições meteorológicas adversas verificadas a nível nacional. Os restantes apenas ocorreram localmente. Os eventos de anomalias negativas ocorreram em menor número. Verificou-se ainda, que os valores mais altos do nível da água do mar registados não resultaram da existência de marés meteorológicas, mas foram devidos às marés vivas. Portanto, a ocorrência conjunta de marés vivas e condições meteorológicas extremas será um risco para as zonas envolventes à laguna, já que poderão ficar sujeitas a inundações.

Keywords Harmonic Analysis, Tidal Propagation, Astronomical Tide, Metereological Tide, Ria de Aveiro.

Abstract Ria de Aveiro is a shallow lagoon, located in the Northwest of Portugal, separated from the sea by a barrier island, with which is connected through an artificial channel fixed by breakwaters. This work aims to study the tidal changes induce by geomorphologic modifications occurred in Ria de Aveiro between 1987/88 and 2017, analysing the variations on the tidal amplitude and phase of tidal constituents: M_2, S_2, M_4, M_6 and MSf. This work also aims to determine the frequency of storm surge phenomena occurrence, between 2012 and 2017, determining which factors influence the generation of the storm - variation in atmospheric pressure, intensity and direction of the wind and precipitation - and verify the increase of the water level in Ria de Aveiro caused by these meteorological events. Data were collected on tidal gauges in the main channels of the lagoon. Annual amplitude and phase variation graphics of tidal constituents: M_2, S_2, M_4, M_6 and MSf (which were computed using the T-Tide Matlab package), were drawn for the different years. This allowed to observe the annual tidal evolution and to verify if there had been any relevant changes during the time interval in which the data collection took place. Annual series of the residual meteorological tide were determined for each year between 2012 and 2017, by subtracting the astronomical predicted tides from the measured tidal signal, and to identify the distribution of the positive and negative anomalies in each station studied, and find the relationship between meteorological variables and the generation of tidal elevations. For this purpose, were drawn graphs of the atmospheric pressure, wind intensity and direction, precipitation and water level and residual graphs. From the results obtained, in general and for each station, the annual amplitude values are increasing while the phase is decreasing. Between 1987/88 and 2002/03 there was an increase in amplitude in the studied stations. This change is a consequence of the increase in the depth of the navigation channels due to dredging operations in 1998. From 2012 to 2017 and after the North breakwater extension there are no significant variations in tidal amplitude or phase. Thus, the extension of the North breakwater did not produce appreciable changes in the tidal dynamics in Ria de Aveiro. By the analysis of the meteorological tide was verified that positive anomalies are more frequent than negative. From the different events occurring between 2012 and 2017, only two positive storm surges influenced the entire lagoon, having been generated by adverse meteorological conditions verified at national level. The remaining were manifested only locally. The events with negative anomalies occurred in a smaller number. From the analysis of all the studied events, it was verified that the higher values of the level of the sea water did not result from the existence of meteorological tides, but from the spring tides. Therefore, the joining of a positive storm event at high tide of spring tides will constitute a high risk for the marginal areas of the lagoon, which may be flooded.

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1. Introduction

1.1. Motivation and Aims

Coastal areas are subject to great natural and anthropogenic pressures. Due to their physical characteristics, these areas provide exceptional conditions for biological productivity, as well as industry, commercial and urban development. Ria de Aveiro is an example of this, a very important area on the Portuguese coast that provides natural conditions for harbour, navigation, industry and recreational facilities, but also offers good conditions for agriculture and aquaculture. Because of these exceptional conditions, it is a densely populated place that intensifies anthropogenic pressures.

Ria de Aveiro is highly influenced by marine and fluvial interaction (Plecha *et al*, 2014), being a dynamic system strongly dependent on tidal action. The lagoon has been subject to several changes, not only caused by nature, which include the effects of storms, winds, tides and sea level rise, on the local erosion and deposition, but also by anthropogenic factors, which are generally related to fishing, agriculture, tourism and coastal works (Vaz and Dias, 2011). Over the last years its geomorphology has undergone changes that will specifically affect their tidal characteristics, making these systems more vulnerable to risks of flooding and increasing the salinization of the adjacent land, as well as hindering the navigation in the shallow channels. The propagation of tides in coastal environments, heavily depends on their morphological configuration (Dias and Picado, 2011), so a constant motorization of these natural systems is necessary in order to predict the consequences caused in their hydrodynamics and thus to intervene with some anticipation, since these natural systems are of such socioeconomic importance.

The extreme meteorological factors are also important in the dynamics of the estuary, as these will affect the meteorological tide, which is directly related to atmospheric pressure, wind and precipitation, having an impact in the water level elevation, particularly in shallow areas such as Ria de Aveiro. At times, these conditions interact in a complex way to increase or decrease the water levels significantly above or under predicted tide heights. Storm surges generated through these meteorological conditions induce great navigational and other hazards, such as the flooding of adjacent land (Ribbat, 2012). Another factor that can cause flooding is the long periods of strong winds, which can induce water accumulation on one side of the channels.

This thesis intends to study the tidal changes induced by geomorphologic modifications between 1987/88 and 2017, using the analysis of tidal constituents: M_2 (semi-diurnal lunar tide), S_2(solar-semi diurnal tide), M_4 (quadric-diurnal tide), M_6(hexa-diurnal tide) and MSf (long period tide) in several channels of Ria de Aveiro.

This thesis also aims to determine the frequency of storm surge phenomena occurrence, between 2012 and 2017, determining which factors most influence the generation of the storm - variation in atmospheric pressure, intensity and direction of the wind and precipitation - and to verify the increase in water level in Ria de Aveiro caused by these meteorological events.

1.2. Work Structure

This MSc thesis includes six Chapters.

Chapter 1 presents the motivation and aims, the structure of this work and the state of the art about the problem that is researched.

Theoretical concepts about astronomical and meteorological tides is described in Chapter 2.

In Chapter 3 are described the main characteristics and location of Ria de Aveiro.

The description of the methodology followed in this work is presented in Chapter 4, including the details about the water level and the meteorological data, and also the data processing analyses (tidal harmonic and non-tidal components).

Chapter 5 includes the results and the discussion concerning the tidal components analysed in this work – tidal harmonic analysis and meteorological residual analysis.

Finally, the main conclusions are presented in Chapter 6.

1.3. State of the Art

Coastal systems are natural environments of extreme importance, not only because of their biological richness, but also because they are places with optimal conditions to accommodate infrastructures of various sectors, namely agricultural, port, industrial and recreational, among others. Consequently, these coastal systems are constantly suffering with pressures of natural and anthropogenic origin.

The understanding of the evolution of the lagoon systems at several levels, as biological, chemical, physical and others, led the scientific community to carry out several studies that later resulted in several publications. Ria de Aveiro is an example of this, as can be verified by the large number of works on physical processes that have been published over the years, mainly resulting from numerical modelling simulations.

One of the first studies carried out on hydrological characterization of Ria de Aveiro was done by Dias *et al* (1999), where authors concluded that the astronomical tide is the main forcing agent driving water circulation in the lagoon. The tide is semidiurnal and the tidal wave propagation in the lagoon has the characteristics of a damped progressive wave. The lunar principal, M_2, and the solar principal, S_2, are the main tidal constituents. These authors also showed that Ria de Aveiro can be considered as vertically homogeneous, except occasionally when fresh water inflows are high, and the upper parts of the lagoon can present vertical stratification.

Properties of tide and tidal currents in Ria de Aveiro are characterized and discussed by Dias *et al* (2000). These authors showed that tide propagates from the inlet are present in the entire lagoon. There is a tidal distortion inside the lagoon and during the propagation the tidal wave amplitude decrease and the phase lag increases, results also found by Araújo (2005), the author compared amplitudes and phases values between 1987/88 and 2002/03. This author also determined that until 1987/88 most of the lagoon was flood-dominant, and since then the central section of Ria de Aveiro has become ebb-dominant, while the northern and southern sections remain flood-dominant. Dias (2011) pointed out that the deepening of the inlet channel and surrounding area is one of the main causes for the changes in the characteristics of the tide that have been reported by several works about this topic (Dias *et al*. (1999), Dias *et al* (2009) and Araújo (2005)).

To evaluate the effects on the Ria de Aveiro hydrodynamics due to changes in several natural and anthropogenic factors over the last years, other studies have been carried out. Dias and Picado (2011) studied the tidal dynamics changes induced by morphologic anthropogenic and natural modifications in channels depth and geometry of Ria de Aveiro. Their results of the model used, suggest that the amplitude of the tidal constituents M_2 and K_1 has increased and its phase has decreased in response to the increased depth of the inlet channel. When an enlargement of the flooded area is assumed, a slight decrease in tidal amplitude and an increase in phase lag are observed. The tidal prism at the lagoon mouth has increased from the past to the present and the enlargement of the flooded area also increased the tidal prism. Similar conclusions were presented by Picado *et al* (2011) in relation to the increase of the flooded area. In this work, the authors also evaluated the consequences of the mean sea-water rise in the hydrodynamics of the Ria de Aveiro. This results in the amplitude increase and a phase decrease, as well as increasing flood and ebb currents and in the dominance of ebb (flood) in the central zone (upstream). Lopes *et al* (2013) also studied the changes induced by local morphological modifications in flooding extension, as well as in the tidal prism, between 1987 and 2012. These authors concluded that the lagoon deepening observed led to a generalized increase in the extension of the lagoon flooded area as well as in the tidal prism, making the lagoon more vulnerable to oscillations.

Recently, Dias (2016a) presented results of investigations carried out mainly using numerical modelling techniques. The main objective was to characterise and study the temporal evolution of the tide in the Ria de Aveiro, between 1987/88 and 2012, in the context of the geomorphological evolution of the lagoon. During this time, a significant amplification of the tidal amplitude and its faster propagation along the lagoon main channels was identified. It was concluded that the properties of the tide in the Ria de Aveiro near the inlet are strongly dependent on the characteristics of the oceanic tide. Therefore, smaller differences are identified in the central area of the lagoon, which are larger in the head of the main channels. It was also verified that the evolution of the tide in the Ria de Aveiro is extremely influenced by the induced geomorphologic changes, both of natural and anthropogenic origin. This results in the increase of the tidal amplitude and in the decrease of the phase verified in the last decades, which are in part a consequence of the deepening of the inlet channel and the main channels of the lagoon. Another variable studied was the increase in the floodable area of the lagoon, that indirectly leads to an increase in the inlet channel depth. This responds to the intensification of dominant ebb currents in this zone, which in the future may lead to an increase in the tidal amplitude.

The morphological evolution of the Ria de Aveiro inlet was analysed by Plecha *et al* (2011), since 1987/88, three years after the conclusion of the works for the configuration of the breakwaters, to 2005. It was found that the inlet channel deepening was motivated by the new inlet configuration, which changed the sediment dynamics and the region that surrounds the North jetty, putting at risk the stability of this structure. The residual sedimentary fluxes at the entrance channel are mostly directed offshores and significantly lower than observed at the nearshore area, evidencing the lagoon capacity to export sediments. Also, the impact of the extension on the inlet breakwaters (200 meters in 2012) on the hydrodynamics of Ria de Aveiro was studied by Dias and Mariano (2011) through a numerical modelling approach. This work shows that the jetty extension slightly changes the local hydrodynamic patterns, and may induce modifications in the overall lagoon circulation related with the tidal prism decrease found for the main channels.

Coastal hazards, such as inundation and coastal erosion, caused by natural or anthropogenic factors, have been widely studied all over the world due to their harmful consequences. The main natural cause of coastal hazards arises from weather extremes, such as storm surges and the cycles in ocean-atmospheric response (see level and currents). The dependence of this phenomenon on the wind and on the variation of the atmospheric pressure was made by Pore (1963), who studied the relation of these two meteorological factors with the extratropical storm surges in Atlantic City. It was also defined by this author that meteorological tide (storm surge) is the algebraic difference between the observed and the predicted tides, which is considered to be the meteorological effect on sea level.

Ribbat (2012) also related the effect of wind and atmospheric pressure on the formation of storm surges in Torres Strait, Australia. This author found that the response of residual sea level to barometric pressure is most significant during periods of low pressure systems, but in relation to the wind these phenomena depends on the wind speed, direction and duration. This work also concluded that the wind would be least influential in these events.

Overelevation of the tide due to meteorological effects has also been subject of studies in Portugal, since it is an important factor for the occurrence of floods, namely in Ria de Aveiro. Tidal exchanges are continuous and predictable as they are periodic. However, subtidal process are less predictable as they are generated by meteorological forcing.

Processes affecting the exchanges between lagoons and the adjacent inner continental shelf are controlled by tidal and subtidal oscillations. Dias and Fernandes (2006) studied the propagation of tidal and subtidal oscillation throughout the access channel of Patos Lagoon (Brazil) and the main channels of Ria de Aveiro Lagoon. For Ria de Aveiro, the tidal energy is stronger than the subtidal energy, propagating into the far end of channels. The semidiurnal and diurnal tidal signals are similarly attenuated, whereas the quarter-diurnal signal is essentially generated inside the lagoon. The subtidal energy is usually very low, however the energy is amplified along the lagoon channels when associated with sporadic extreme weather events connected with coastal sea-level changes or high river discharge.

Taborda and Dias (1992) analysed storm surge during two storms in February/March 1978, and in December 1981, on the Portuguese coast. They characterised these storms using tide gauge data (Viana do Castelo, Leixões, Aveiro, Cascais, Lisboa, Tróia, Sines and Lagos) and predicted astronomical tide to calculate the meteorological tide, founding a relationship between the surge levels with the atmospheric pressure variations and the wind speed and suggest that the surge levels were mostly related with the local meteorological conditions.

The work developed by Picado *et al* (2013) had as principal aim to evaluate the storm surges amplitude impact in the hydrodynamics of Ria de Aveiro lagoon, through numerical modelling simulations. These authors concluded that the most significant changes occur at the main channels head for all return periods analysed (2, 10 and 100 years), revealing that these regions are the most vulnerable to marginal flooding. Also, storm surges induced higher velocities and tidal prism in the lagoon, increasing the marginal erosion risk, as well as the salinization of the lagoon marginal lands.

Coastal wave regime is also important, mainly in lagoons such as the Ria de Aveiro, because they are exposed to a highly energetic wave climate. Vaz *et al* (2013) studied the influence of the coastal wave regime at the inlet channel dynamics and concluded that although the dominant forcing of Ria de Aveiro inlet hydrodynamics is the tide, the sea level and current velocity fluctuations depend also on the wave regime. Consequently, the storm events induce important waves set-up that may change the inlet hydrodynamics.

To study the consequences of the extreme sea levels caused by the combination of high tides, storm surges and wind-generated waves, was one of the aims of Lopes (2016) Ph.D. Thesis. This author analysed the influence of the simultaneous occurrence of high tide and storm surges on the risks of flooding, especially when these phenomena occur in neap or spring tide conditions. This work concluded that the most intense storm surge events do not always induce extreme sea levels, since they depend also on the tidal level. Also, were not found significant evidences that climate changes would modify tidal and storm surge levels in the Ria de Aveiro adjacent coast.

2. Theoretical Concepts

As will be discussed in the following theoretical concepts, gravitational forces of the Moon, Sun and Earth are the main causes of short-term sea level fluctuations throughout ocean basins, known as tidal movements. These movements are termed astronomical tides, because of the forces already mentioned. Other stimuli impacting sea level elevation is the meteorological forcing (atmospheric pressure, wind stress and precipitation), that in certain conditions interact in a complex way to elevate or reduce water levels significantly above or under predicted tidal heights, known as storm surges. Any sequence of measurements of sea level elevation will have a tidal component (astronomical tide) and a non-tidal component (meteorological tide).

A review of theoretical concepts about astronomical and meteorological tides is performed in this section.

2.1. Astronomical Tides

Since the Earth rotates around its axis, the effects of the interaction between gravitational pulling forces of the Moon and the Sun on Earth, and the centrifugal derived from the system rotation is responsible for the generation of the astronomical tide. The tide generated force (resulting from the interaction between the gravitational force and the centrifugal force) acts directly over the ocean, generating waves characterised by a long period. The movements originated by these forces are termed as gravitational or astronomical tides. These progress to the coast, where, due to the reduction of depth, it is possible to identify them by the regular rise and fall of the surface of the sea. This periodic vertical movement of water on the surface of the Earth is frequently known as tide.

The concept of tide can be understood as the sum of many constituents or partial tides, where the respective periods correspond to the period of one of the astronomical movement between the Earth, the Sun and the Moon.

Each harmonic constituent can be described mathematically in terms of amplitude and period by:

$$A(t) = H_n \cos(\omega_n t - g_n) \qquad , \qquad (2.1)$$

where A is the value of the variable elevation at time t, H_n is the amplitude of the oscillation, ω_n is the angular velocity which is related to the period T_n, and g_n is the phase lag relative to some defined time zero, and t is time. The time zero for g_n is often taken as the phase lag on the Equilibrium Tide phase at the Greenwich Meridian (Pugh, 2004). The different harmonic constituents obtained by the harmonic analysis allows the prediction and determination of tidal characteristics.

A tide is considered ideal if it presents two high tides and two low tides of uneven height during a lunar day. However, such scenario does not happen in all places due to changes caused by different depths, dimensions and shape of the ocean basins. Therefore, tides have different characteristics, namely diurnal tide, semidiurnal tide or mixed tide.

Tidal wave distortions are usually expressed as simple constituents with frequencies that are multiple, sums or frequency differences of fundamental harmonic constituents.

In addition to the diurnal tidal cycle, there is also a fortnight cycle due to the changing position of the moon's relative to earth. When the moon is New or Full, the spring tides occur, with an approximate period of two times a month, and are characterized by an increase in tidal range. Neap tides, with small tidal range, occur near the time of the first and last lunar quarters, between spring tides.

2.2. Meteorological Tides

The sea-level is characterised by having a tidal (astronomical tide) and a non-tidal component (meteorological tide). The non-tidal component is the part of the sea level that remains once the astronomical tidal component has been removed and is called the residual or meteorological residual (Pugh, 1996).

The general representation of the observed level, $X(t)$ that varies with time may be written by the following equation:

$$X(t) = Z_0(t) + A(t) + M(t) \quad , \qquad (2.2)$$

where $Z_0(t)$ is the mean sea level, which changes very slowly with time, $A(t)$ is the astronomical part of the variation and $M(t)$ is the meteorological surge component.

From Equation (2.2), the meteorological tide is the difference between the observed and the predicted sea levels at a given time t:

$$M(t) = X(t) - Z_0(t) - A(t) \quad . \qquad (2.3)$$

The term meteorological tide, or storm surge, is used for the excess sea levels generated by a severe storm, produced by meteorological causes (atmospheric pressure gradient and extreme near-surface wind stress) (Pugh, 2004). These two meteorological effects, the atmospheric pressure gradient and the wind tension parallel to the surface of the sea water, are the main factors responsible for the occurrence of over-elevation of the water. However, there are others that when occurring simultaneously with those mentioned above, may increase storm surges, such as the occurrence of spring tides, an increase of precipitation that drives to an increasing of river flow, and the formation of waves due to wind.

The water movement can be described by hydrodynamic equations, which are defined considering a Cartesian coordinate system, with x and y axis in the horizontal plane and the z axis directed vertically upwards, and zero level for vertical displacements is taken as the long-term mean sea-level. The momentum equations are:

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p_a}{\partial x} - g\frac{\partial}{\partial x}(\zeta - \bar{\zeta}) + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z}, \qquad (2.4)$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p_a}{\partial y} - g\frac{\partial}{\partial y}(\zeta - \bar{\zeta}) + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z}, \qquad (2.5)$$

and the continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \qquad (2.6)$$

where ζ is the free surface elevation, u and v are the horizontal velocity components, ρ is the water density, g is the gravitational acceleration, f is the Coriolis parameter, p_a is the atmospheric pressure, τ_x and τ_y are the frictional terms arising from shear stress across horizontal planes and $\bar{\zeta}$ is the tide-generating potential.

By integrating through a vertical water column from the bottom $z = -h$ to the surface $z = \zeta$ and defining the components U, V of the volume transported by the following two equations:

$$U = \int_{-h}^{\zeta} u \, dz, \qquad (2.7)$$

$$V = \int_{-h}^{\zeta} v \, dz. \qquad (2.8)$$

The depth-integrated equations may be obtained as:

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}\left(\frac{U^2}{h+\zeta}\right) + \frac{\partial}{\partial y}\left(\frac{UV}{h+\zeta}\right) - fV = -\frac{(h+\zeta)}{\rho}\frac{\partial p_a}{\partial x} - g(h+\zeta)\frac{\partial}{\partial x}(\zeta - \bar{\zeta}) + \frac{\tau_{sx} - \tau_{bx}}{\rho}, \qquad (2.9)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}\left(\frac{UV}{h+\zeta}\right) + \frac{\partial}{\partial y}\left(\frac{V^2}{h+\zeta}\right) + fU = -\frac{(h+\zeta)}{\rho}\frac{\partial p_a}{\partial x} - g(h+\zeta)\frac{\partial}{\partial y}(\zeta - \bar{\zeta}) + \frac{\tau_{sy} - \tau_{by}}{\rho}, \qquad (2.10)$$

and

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial \zeta}{\partial z}=0. \quad (2.11)$$

The velocity components u and v, and the transport components U and V refer to the tidal constituents and the meteorological effects. In coastal waters of limited extent, the direct effects of the tide-generating potential, represented by $\bar{\zeta}$, can be neglected. The components τ_{sx} and τ_{sy} are the tangential shearing stress of the wind on the sea surface. τ_{bx} and τ_{by} represent the components of stress at the bottom (Bowden, 1984).

As already mentioned, the effect of atmospheric pressure and wind are the main factors for the occurrence of a storm surge. Therefore, it is necessary to analyse separately how sea water behaves with the variations of these two factors: atmospheric pressure and wind stress.

2.2.1. Atmospheric Pressure Effect - Inverted Barometer Effect

Changes in atmospheric pressure may increase or reduce the sea level height, depending on the type of prevailing system. As a result of the inverted barometric effect, low pressure systems elevate sea levels, while high pressure systems tend to depress them (Ribbat, 2012). The physical behaviour of this barometric effect can be explained considering equation (2.9), neglecting the effect related to the term $\tau_{sx}-\tau_{bx}$, assuming that V = 0 (considering the sides of the channel parallel to the x axis), and consider the variation of ζ throughout the channel is smaller compared to its length. The equation obtained is:

$$\frac{\partial \zeta}{\partial x}=-\frac{1}{g\rho}\frac{\partial p_a}{\partial x} \quad . \quad (2.12)$$

If the variations $\Delta\zeta$ (sea level variations) and Δp_a (local variations of atmospheric pressure) are related to a finite and horizontal displacement Δx, then equation 2.12 becomes:

$$\Delta\zeta=-\frac{1}{g\rho}\Delta p_a \quad , \quad (2.13)$$

in which the decrease in atmospheric pressure is followed by an increase in sea level height, and vice versa (Bowden, 1984).

An increase in atmospheric pressure of one millibar will produce a theoretical decrease in sea water of one centimetre (Pugh, 2004).

2.2.2. Wind Stress Effect

When a storm approaches the coast, the alongshore component of wind stress drives an Ekman setup (the net transport of water by the wind occurs at a 90° angle to the right of the wind vector in the Northern hemisphere) at the coast located to the right-side of the wind. As an important consequence, the coastal region located to the right-side of the storm track usually suffers larger storm surge and damages than the coastal region located to the left side (Bertin, 2016).

Considering the accumulation of sea water on the Portuguese coast, the entrance of seawater into Ria de Aveiro can increase significantly in response to Ekman transport, induced by southward winds. Since the tidal wave in the lagoon is forced by the oceanic tide, an increase in water level inside the lagoon is observed.

The surface currents generated by the wind stress behave differently depending on the depth of the site being studied. For a wind blowing along a narrow channel of constant depth, the steady-state effect of wind drag on the slope of the sea surface is to pile up water up at the downwind end and to produce higher sea levels there. This can result from a balance between the wind stress and the pressure gradient that opposes it (Pugh, 2004).

Considering a closed channel at one of its ends, and that the bottom stress is near zero and considering a small ζ compared to the height of the water column h, equation (2.9) can be reduced to:

$$\frac{\partial \zeta}{\partial x} = \frac{\tau_{sx}}{g\rho h} \quad , \qquad (2.14)$$

Where $\frac{\partial \zeta}{\partial x}$ is the slope formed in the sea water due to wind, and τ_{sx} the effective tangencial stress of the wind on the sea surface (Bowden, 1984). The equation of τ_{sx} is:

$$\tau_{sx} = C_D \rho_a W^2 \quad , \qquad (2.15)$$

where W is the wind speed measured at a given height, usually taken 10 m above the sea surface, ρ_a is the density of the air and C_D is a dimensionless drag coefficient (Bowden, 1984).

By integrating equation (2.14) through the horizontal length L:

$$\zeta = \int_0^L \frac{\tau_{sx}}{g\rho h} dx = \frac{\tau_{sx}}{g\rho h} L \quad , \qquad (2.16)$$

From the equation (2.16), it can be verified that when the wind blows along a channel the effect on the slope of the water, due to its accumulation, will be higher than if the wind blows perpendicular to the channel.

Also, by using equations (2.14) and (2.15), the following is obtained:

$$slope = \frac{Increase\ in\ level}{Horizontal\ distance} = \frac{C_D \rho_a W^2}{g\rho h} \quad . \qquad (2.17)$$

Formula (2.17) mathematically represents the important fact that the wind effect on sea levels increases inversely with the water depth h (Pugh, 2004).

A comparison between the elevation generated by the wind stress and by the direct atmospheric pressure, estimated by equation (2.13), indicates that for depressions in mid-latitude the wind stress effect is usually an order of magnitude higher than the pressure effect (Bowden, 1984).

3. Study Area: Ria de Aveiro

Ria de Aveiro (Figure 1) is a shallow water coastal lagoon system, located on the northwest coast of Portugal (40°38'N, 8°44'W), separated from the sea by an extensive sand bar and integrated in the Vouga river basin. It is 45 km long and 10 km wide, covering an area of 89.2 km^2 at a high spring tide, which is reduced to 64.9 km^2 in neap tide conditions (Dias, 2001; Lopes *et al*, 2010). It has a very irregular and complex geometry, characterised by narrow channels, large areas of mud flats and salt marshes. The lagoon has also four main channels: Mira Channel, Ílhavo Channel, Espinheiro Channel and S. Jacinto Channel.

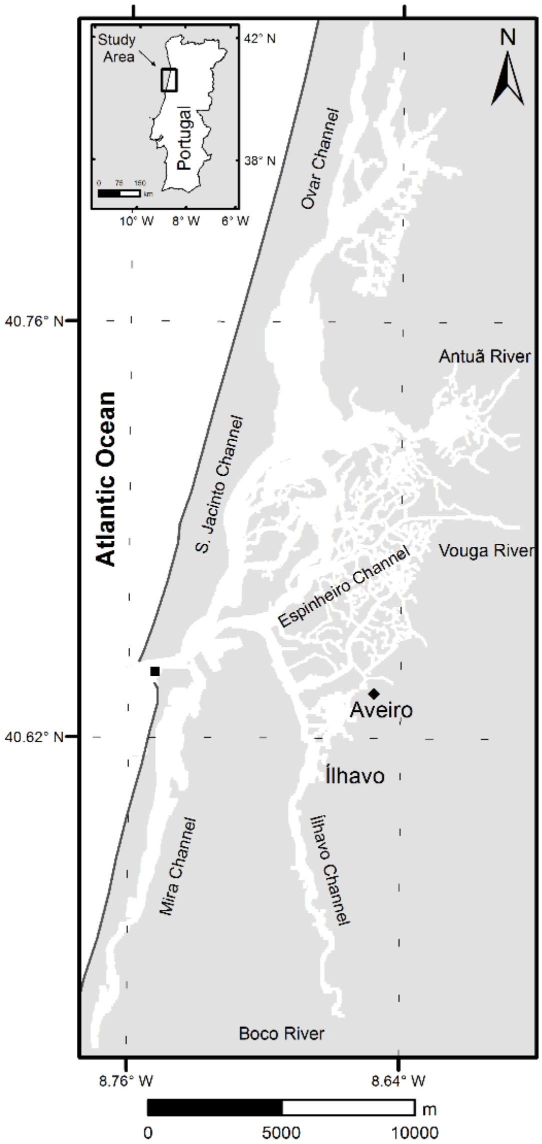


Figure 1 – Map of the Ria de Aveiro, with the location of the main channels and freshwater sources.

The average depth of the lagoon is about one meter, except in the navigation channels where dredging operations are frequently carried out. The channel connecting the lagoon with the

Atlantic Ocean has a depth higher than twenty meters and the other navigation channels are about seven meters deep. The inlet channel has approximately 1.3 km long and 350 m wide and is fixed by the North and South breakwater (Dias *at al*, 2000, Picado *et al*, 2011).

The lagoon receives freshwater from the following rivers: Vouga river (draining in the Espinheiro Channel, and representing the main source of freshwater to the lagoon), Antuã river (draining in the Laranjo basin, the second most important river), Boco river (draining in the Ílhavo Channel), Cáster, Gonde and Fontela rivers (flowing in the S. Jacinto Channel) and various effluents flowing into the upstream end of the Mira Channel (Dias, 2001).

The lagoon hydrodynamics is tidally dominated by the influence of the oceanic tide, which is predominantly semidiurnal with a small diurnal pattern (Dias, 2001). The astronomical tidal range varies between a maximum of 3.2 m in spring tide and a minimum of 0.6 m in neap tide, with an average value of 2 m, whereby the lagoon should be classified as mesotidal (Dias *et al*, 2000). Although infrequent, the meteorological tide can reach a maximum height of $\sim$1 m (Picado *et al*, 2013). Concerning tidal asymmetry, until 1987/88 most of the lagoon was flood-dominant (Araújo *et al*, 2008). Since then, the lagoon is ebb dominant at the mouth and flood dominant at the upper part. As the lower lagoon is ebb dominant, there is a tendency to export sediments to the ocean (Dias, 2001; Oliveira *et al*, 2006; Picado *et al*, 2013). The lagoon can be considered as vertically homogeneous, except occasionally when fresh water inflows are high, and the upper parts of the lagoon can present vertical stratification (Dias *et al*, 2000).

In addition to the oceanic tide and rivers flows, the wind stress also determines the dynamics of Ria de Aveiro. The wind action, which can last from a few hours to a few days, may induce slight changes on local hydrodynamics. This can happen, especially in shallow areas and wide channels, inducing currents, surface waves and mixing processes in the water column (Dias, 2001).

Anthropogenic action was the dominant factor in the morphological evolution of the lagoon in the recent past and also affected directly the natural geomorphological evolution of the lagoon (Picado *et al*, 2011). The most noteworthy human intervention was the creation of an artificial inlet in 1808, in response to persistent accretion of the natural inlet, and later the construction of two breakwaters (Lopes *et al*, 2013; Lopes, 2016). The works to extend of the northern breakwater that fixes the lagoon entrance, one in 1987 and the other in 2012; the regular dredging activities in the inlet channel and in the lagoon main channels, between 1996 and 1999; and the natural destruction of great part of the salt pans, due to its lack of preservation, changed the bathymetry and the geometry of the lagoon channels (Lopes, 2016). As result, the lagoon became deeper and as consequence the tidal wave amplitude increased, and its propagation became faster (Lopes and Dias, 2015). These morphological changes induce modifications in the lagoon hydrodynamics.

4. Methodology and Data

The analysis of water level time series recorded by tide gauges is fundamental in understanding the Ria de Aveiro tidal dynamics. However, tidal signals are a complex combination of the oscillations generated by the gravitational forces of the Moon and the Sun acting on the sea water, and irregular oscillations due to atmospheric variability. The separation from non-tidal to tidal energy is a crucial component in any analysis of water level time series, especially in coastal waters.

This chapter will describe where and when the sea level and the meteorological data used was obtained, as well as the methodologies that were used to analyse them.

4.1. Data Presentation

4.1.1. Sea Level Data

This study was carried out using records by tide gauges located in the main channels of Ria de Aveiro, which geographical location is represented in Figures 2 and 3 and in Table 1, in three different time intervals: 1987/88, 2002/03 and 2012 to 2017. This allowed to determine the possible variations in the tidal characteristics between these periods.

In 1987/88 and in 2002/03, the sea surface elevation (SSE) used were obtained in the context of general surveys carried out by the Instituto Hidrográfico Português and by the University of Aveiro, respectively. In these two-time intervals, the data collection was done only during some months. Between 2012 and 2017, the data were collected monthly and continuously through tide gauges installed along the Ria de Aveiro as part of the monitoring of the North breakwater extension, carried out by Administração do Porto de Aveiro (APA), except for several malfunctions of the tide gauges at each station, which caused gaps in sea level measurements (Table 7).

Sea level observations were recorded with a hourly frequency for 1987/88 and 2012, 6 minutes between 2002 and 2003, and 20 minutes for the years of 2013 to 2017, except for Barra station that where sampled every 5 minutes.

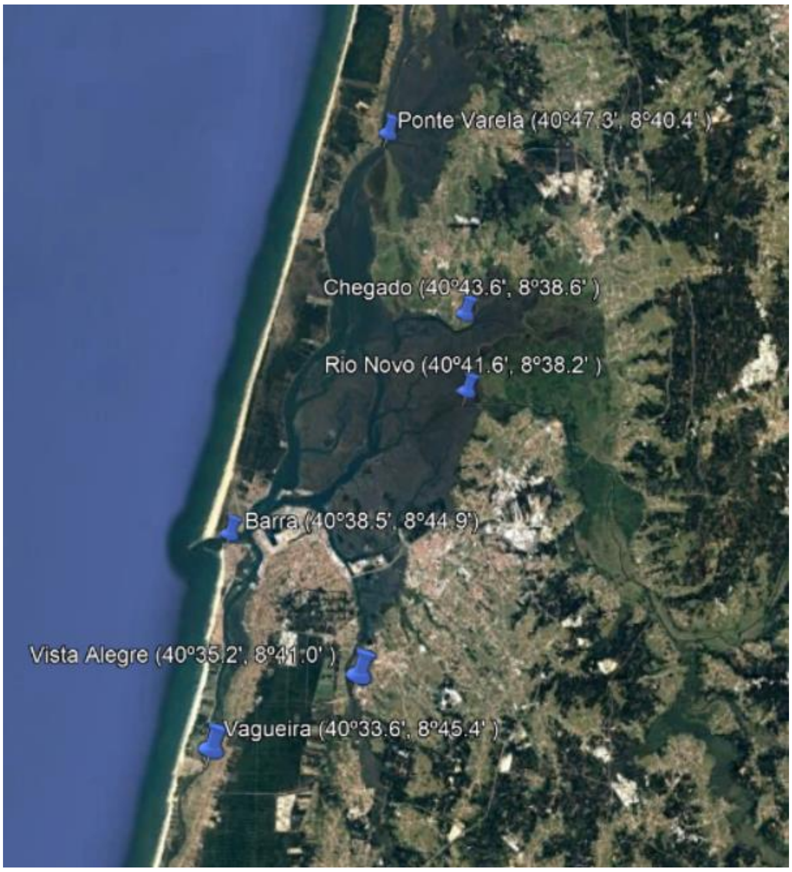


Figure 2 - Geographical position of each tide gauge in Ria de Aveiro (Google Earth, 2017).

Table 1 - Observation periods and geographical location of the tide gauges.

Station/ year	**1987 /1988**		**2002/2003**		**2012/2017**		**Lat.**	**Long.**
	Start	**End**	**Start**	**End**	**Start**	**End**	**North**	**West**
Barra	13/05/87 15:00:00	06/08/87 22:55:12	07/05/03 09:48:00	06/08/03 13:57:12	01/01/12 00:00:00	31/03/17 23:55:00	40°38.5’	8°44.9’
Ponte Varela	16/06/87 15:00:00	06/08/87 22:55:12	-	-	01/04/12 00:16:00	31/03/17 23:40:00	40°47.3’	8°40.4’
Cais Do Bico Chegado	25/08/87 23:00:00	10/12/87 23:00:00	12/06/03 11:45:31	14/07/03 10:04:43	15/04/12 00:05:00	31/03/17 23:40:00	40°43.6’	8°38.6’
Rio Novo do Principe	31/01/88 23:00:00	13/04/88 23:00:00	08/03/03 12:25:05	11/04/03 01:08:17	01/04/12 00:11:00	31/03/17 23:40:00	40°41.6’	8°38.2’
Vagueira	28/04/87 17:00:00	09/06/87 16:04:48	21/11/02 16:06:29	10/02/03 09:10:17	01/04/12 00:09:00	31/03/17 23:40:00	40°33.6’	8°45.4’
Vista Alegre	26/09/88 20:00:00	08/11/88 12:04:48	09/09/03 23:49:04	09/12/03 09:53:52	01/04/12 00:15:00	31/03/17 23:40:00	40°35.2’	8°41.0’

a) Ponte Varela

b) Chegado

c) Rio Novo do Príncipe

d) Vagueira

e) Vista Alegre

Figure 3 - Photos of the places where the tide gauges are located: a), b) and c) were taken on August 1, 2017; d) and e) were taken on 14th October 2017.

4.1.2. Meteorological Data

Wind speed, wind direction and atmospheric pressure data were obtained from the weather station located at the University of Aveiro. These data were recorded every 10 minutes for consecutive days, from 2012 to 2017, with the exception of January 2013. For this month, the meteorological data was acquired in a meteorological station with the coordinates 40.9517°N; 9.375°W, at 6-hourly time interval.

4.2. Data Processing and Analysis

The SSE data sets were subjected to several data management procedures, as the finding and removal of data gaps, interpolation them to have the same sampling period and to fill some gaps in short time intervals. In the case of long intervals with lack of values, it was assumed that the missing values were zero. Due to several equipment failures, measurements between 2012 and 2017 were not always continuous. These failures include problems in the operation of the tide gauges, but they are also related to changes in the infrastructure on the places where they were placed. The stations most affected were Rio Novo and Vista Alegre. The dates with the measurement failures are present in Table 7.

4.2.1. Tidal Harmonic Analysis

A Fourier analysis was first made to identify the frequencies and to measure the relative energy in the components responsible for the sea level variation at each tide gauge. This analysis allowed to determine which frequencies bands are the dominant and thus to identify the main constituents that influence the circulation of water in Ria de Aveiro. After that, a harmonic analysis was applied using the T-Tide application of Matlab (Pawlowicz *et al*, 2002), for the data of each station. Also, the amplitude and the phase of the tidal constituents were determined annually (corresponding to the total months available for each year, at the different stations).

Initially, the analysis included seven tidal constituents: O_1, K_1, M_2, S_2, M_4, M_6, and MSf, where the symbols represent (Bell *et al*, 2006; Pugh, 2004):

O_1- Principal lunar diurnal tide, with a period of 25.82 hrs. This constituent represents the cycle of maximum declination to minimum declination of the Moon;

K_1–Principal lunisolar diurnal tide, with a period of 23.93 hrs, which arises from Sun and Moon's paths over the Equator being at various inclines or declines (angles) to the Equator line;

M_2 – Lunar semi-diurnal tide, which arises from the direct gravitational attraction of Moon on Earth's waters, with a period of 12.42 hrs;

S_2 – Solar semi-diurnal tide, which arises from the direct gravitational attraction of Sun on Earth's waters, with a period of 12.00 hrs;

M_4 - Shallow water constituent, generated by the non-linear effects of advection with a period of 6.21 hrs.

M_6 - Shallow water constituent, caused by the interaction of the tidal wave with the bottom due to the reduced depth, with a period of 4.14 hrs.

MSf – long period tide, with a value of 14.76 days. This period corresponds to the difference between the spring tides and the consecutive neap tides;

Concerning the constituents O_1 and K_1, although they have high frequencies (referred in 5.1.1) they do not present any relevant tendency towards the aims of this work, as mentioned in Fradinho (2014), so they are not showed in this document. Therefore, in the analysis presented in this work the other five tidal constituents mentioned (M_2, S_2, M_4, M_6 and MSf) will be included.

Annual amplitude and phase variation graphics (section 5.1.2) of each harmonic constant were made in the different years and for the following stations: Barra, Ponte Varela, Chegado (Cais do Bico), Rio Novo, Vagueira and Vista Alegre. This allowed to observe the annual evolution and to verify if there had been any relevant changes during the time interval in which the data collection took place.

4.2.1.1. Form Number Determination

The Form number will be determined in this work for all stations (section 5.2), between 1987/88 and 2017, using equation:

$$F = \frac{K_1 + O_1}{M_2 + S_2} \qquad (4.1)$$

where K_1 (Principal lunisolar diurnal), O_1 (Principal lunar diurnal), M_2 (Lunar semi-diurnal) and S_2 (Solar semi-diurnal tide) correspond to the amplitude of the tidal constituents (Pugh, 2004).

When the variation of F is:

- 0 <F <0.25 the tides are considered semidiurnal;
- 0.25 < F <1.5, mixed - mainly semidiurnal;
- 1.5 < F <3.0 mixed - mainly diurnal;
- F > 3.0 diurnal.

4.2.1.2. Tidal Asymmetry

In section 5.3., tidal asymmetry was determined for all stations.

One way of determining the type of asymmetry from the phase of the constituents M_2 and M_4, is to determine the relative phases of these constituents:

$$\varphi_{M4} = 2\theta_{M2} - \theta_{M4} \quad . \qquad (4.2)$$

where the tidal flow has a flood dominance at 0 ° < φ <180 ° and ebb dominance when 180 ° < φ <360 ° (Friedrichs and Aubrey, 1988).

The term tidal asymmetry usually refers to the tidal wave distortion when it spreads to shallow waters, which may result in periods of unequal flood and ebb (Wang *et al*, 1999).

The distortion of the tide as it propagates from the open ocean into the confinement of estuaries can be represented by the non-linear growth of compound constituents and harmonica of the principal astronomical components (Friedrichs and Aubrey, 1988).

Due to the overlap of these constituents, the elevation of the free surface of the water and the current velocity are distorted from its initial sinusoidal form, giving rise to the asymmetry of the tide. For the specific case where the ebb period is higher than that of the flood, the situation is called flood-dominant, because the highest velocity is reached in the flood. In the opposite case, it is called ebb-dominant (Dias, 2016b).

Tidal asymmetry often plays a key role in determining sediment transport and deposition/ erosion patterns in several tidal dominated estuaries and inlets. The transport of sediments will depend on the maximum velocity. That is, if the maximum velocity is that of the ebb, the sediment exportation is higher, if it is of the flood, there will be a mean sediment transport to the interior of the estuary (Dias, 2016b).

It is important to know the tidal asymmetry in estuaries mainly due to the fact that the navigability of the estuarine channels and the geomorphological evolution will be affected by the sediment transport and accumulation. That is, an estuary with flood dominance may be unable to effectively exhale the sediments, hindering navigability, while an estuary with ebb dominance may maintain a stable configuration.

The phases of these two constituents (M_2 and M_4) are used because the dominant astronomical constituent is M_2, the semi-diurnal lunar tide. Because of M_2 dominance, the most significant overtide formed in well-mixed estuaries, like Ria de Aveiro, is M_4, the first harmonic of M_2 (Friedrichs and Aubrey, 1988).

4.2.2. Non-Tidal component (Meteorological Residuals)

Annual series of the residual tide were determined for each year of the period between 2012 and 2017 by subtracting the astronomical predicted tides from the measured tidal signal, as described in equation 2.3.

Also, standard deviations of the meteorological residual annual series were determined to identify storm surge events. According to the criterion proposed by Pugh (1996), the meteorological tide events can be identified considering that the residual levels are higher than three times the standard deviation (3σ) of the residual series (Pugh,1996, Picado *et al*, 2013). A distinction will be made between positive anomalies, whose residual values are higher than 3σ, and the negative ones, whose values are lower than -3σ.

It was not taken into consideration in this analysis those time intervals where several values were missing (which were due to the lack of values and problems with the malfunction of the tide gauge). These time intervals are presented in Table 7 of the Annex.

To identify the distribution of positive and negative anomalies, in each station studied, and understand the relationship between meteorological variables and the generation of tidal elevations, graphs of the atmospheric pressure, wind intensity and direction, precipitation and water level and residual graphs, were performed, section 5.4.

A selection of the obtained events was made to distinguish those that were generated by the variations of atmospheric pressure and the wind intensity (storm surge), and those that were formed due to other effects, namely the occurrence of spring tides. Of the events considered storm surges, were still considered those that formed remotely and that affected all the lagoon, and those that were formed locally.

5. Results and Discussion

Pawlowicz *et al* (2002) show that the separation of tidal and non-tidal energy is a crucial component in any analysis of oceanic time series, especially in coastal waters. Based on this principle, in this Chapter the results obtained from the analysis of the data collected at six tide gauges located in Ria de Aveiro, will be presented and discussed with the aim of studying the astronomical tidal changes induced by geomorphological modifications over time and determining the frequency and main meteorological drivers of the storm surge phenomena, either remotely generated or locally generated.

5.1. Tidal Analysis

5.1.1 Fourier Spectrum

A Fourier analysis was used to identify the frequencies and to measure the relative energy of components responsible for the sea level variation at each tide gauge. This analysis allowed to determine which are the dominant frequencies band and thus to identify the main constituents characterizing the tidal properties in the Ria de Aveiro. Fourier spectra for each gauge is presented in Figure 4.

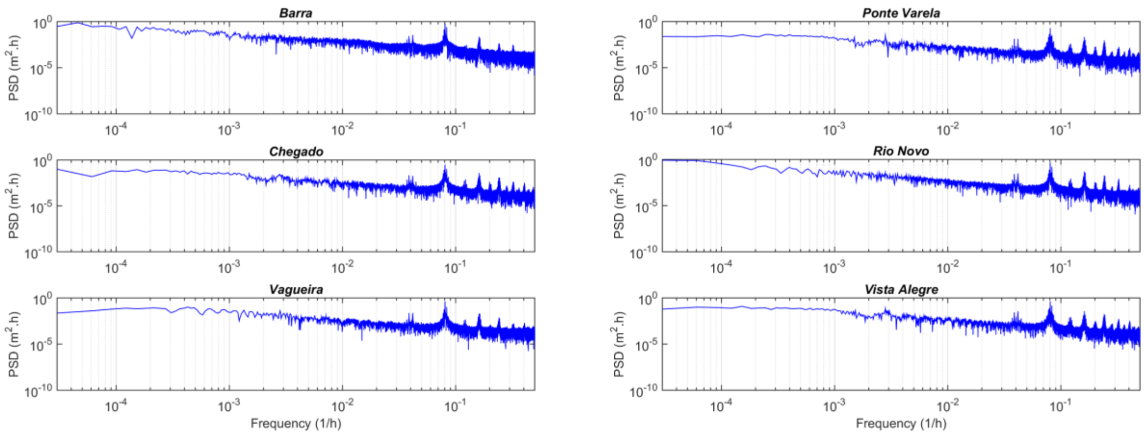


Figure 4 – Fourier spectra for each gauge sites used in sea-level analysis, from 2012 to 2017. These spectra have frequency as their abscissa (x-axis) and power spectral density (PSD), which is a measure of energy, as their ordinate (y-axis).

Through the analysis of the six spectra (Figure 4), were not found high differences between the tidal dominant frequencies for each station. In all of them the semi-diurnal frequency processes dominated the tidal forcing, followed by the diurnal tidal frequencies. In the region where the frequencies are between 10^{-1} h^{-1} to 1 h^{-1}, corresponding to the frequencies of the shallow water constituents, it is possible to verify that the quarter-diurnal tidal frequencies have the highest energy, followed by sixth-diurnal tidal frequencies. The only observable differences between the spectra for all stations are related to the frequencies of the long-period constituent, which frequency band is smaller in Rio Novo.

Normally the residual process is less energetic (left-hand side of plots), except in situations of extreme weather events, when the meteorological tidal frequencies are amplified (Dias and Fernandes, 2006). High energy values at the low frequencies are present in all of spectra because they were obtained in a large time interval during which have occurred storm surge events, with Rio Novo presenting the highest energy values in this frequency range. This may be related with high precipitation and therefore high discharges from Vouga River.

Dias and Fernandes (2006) studied the energy spectrum for stations located between the mouth of the lagoon and throughout the main channels of Ria de Aveiro in 1987 and 1988. They also conclude that the main frequencies were semi-diurnal, followed by diurnal and quarter-diurnal tidal frequencies at the mouth of the lagoon. The energy spectrum for stations located throughout the main channels present similar patterns, although the energy associated with diurnal and semi-diurnal frequencies is lower. These authors showed that these tidal oscillations are progressively attenuated as they propagate landwards. The energy on quarter-diurnal frequencies for these stations are higher than at the mouth, indicating that these frequencies are amplified inside the lagoon. The reason for this is that as primary tides propagate into shallow water regions, the shape of the wave changes and the frictional effects become more pronounced.

5.1.2. Tidal Harmonic Analysis - Amplitude and Phase Analysis

To understand the temporal evolution of each tidal constituent M_2, S_2, M_4, M_6 and MSf, at each tide gauge were analysed between 1987/88 and 2017.

5.1.2.1. Tidal constituent $\boldsymbol{M_2}$

Figures 5 to 14 present the temporal evolution of the amplitude and phase of the tidal constituents studied between 1987 and 2017.

a) Amplitude

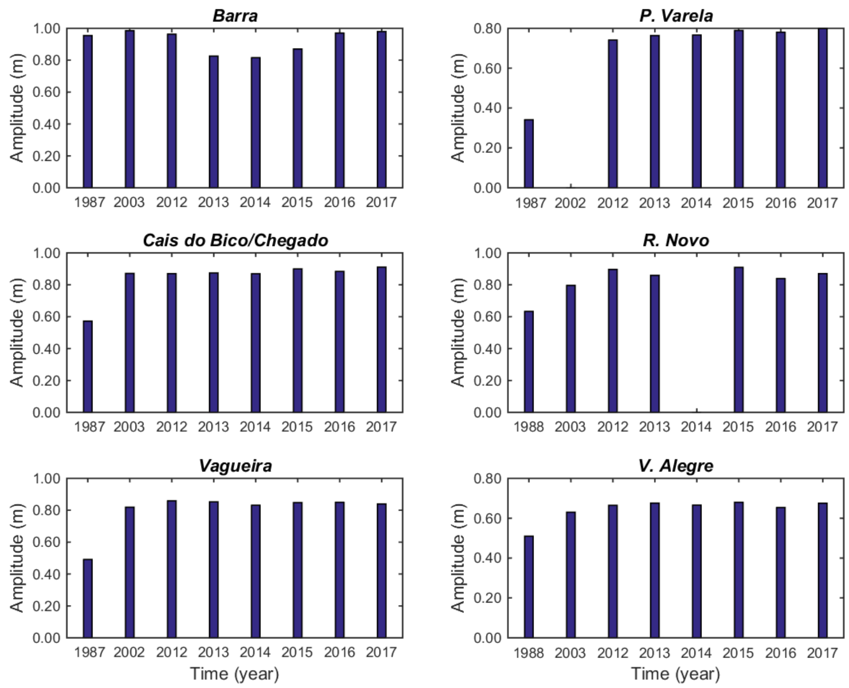


Figure 5 – Amplitude of tidal constituent M_2 in all tide gauges, from 1987/88 to 2017.

The analysis of the amplitude temporal evolution for the stations (Figure 5) revealed an increase of the tidal constituent M_2 between 1987/88 and 2002/03 in all stations. The amplitude difference between 2002/03 and 2012 is not significant, although there is a slight increase in all stations located throughout the main channels, except in Barra where there is a small decrease. From 2012 to 2017, the amplitude does not change significantly, apart from Barra, where a decrease between 2012 and 2015 was observed.

It should be noted that, although there is no data for the year 2002/03 at Ponte Varela, the general trend of the other stations will be considered in the discussion of the results.

The amplitude increases from 1987/88 to 2002/03 are of the order of 32.80 cm in Vagueira, 29.92 cm in Cais do Bico/Chegado, 16.32 cm in Rio Novo, 12.06 cm in Vista Alegre and 3.06 cm in Barra.

b) Phase

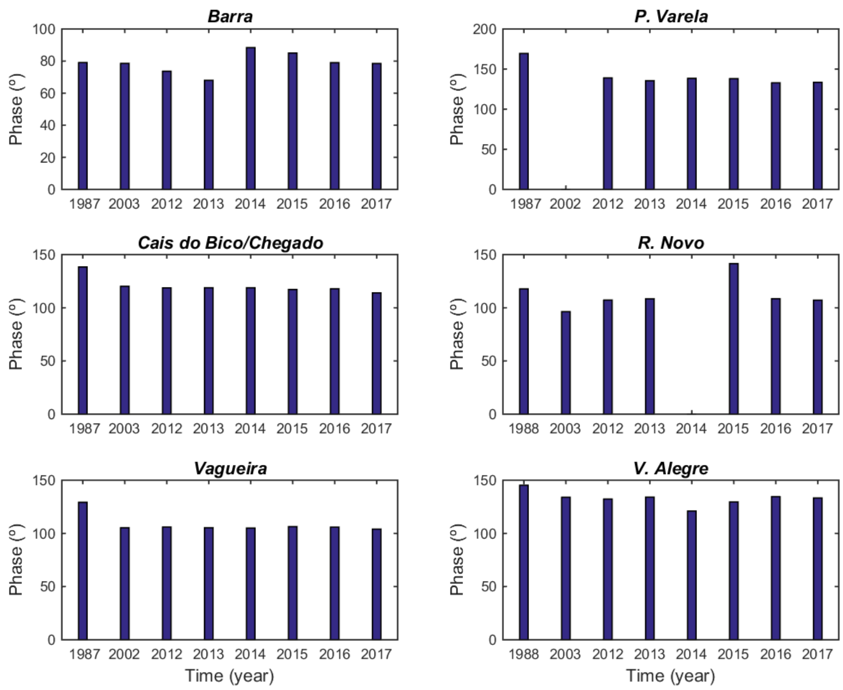


Figure 6 – Phase of tidal constituent M_2 in all tide gauges, from 1987/88 to 2017.

Regarding the phase of M_2 constituent (Figure 6), a decrease was found, in all stations over time, from 1987/88 to 2002/03. For the time interval from 2002/03 to 2017, the phase does not change significantly.

The decrease of the phase, between 1987/88 and 2002/03, was in the order of 23.88° (49.4 min) in Vagueira, 18.20° (37.67 min) in Cais de Bico/Chegado, 21.49° (44.48 min) in Rio Novo, 11.28° (23.35 min) in Vista Alegre and 0.49° (12.20 min) in Barra.

Similar results were found by Araújo *et al* (2008), from 1978/88 to 2002/03, with an increase in amplitude and a decrease in phase for the harmonic constituent M_2.

5.1.2.2. Tidal constituent S_2

a) Amplitude

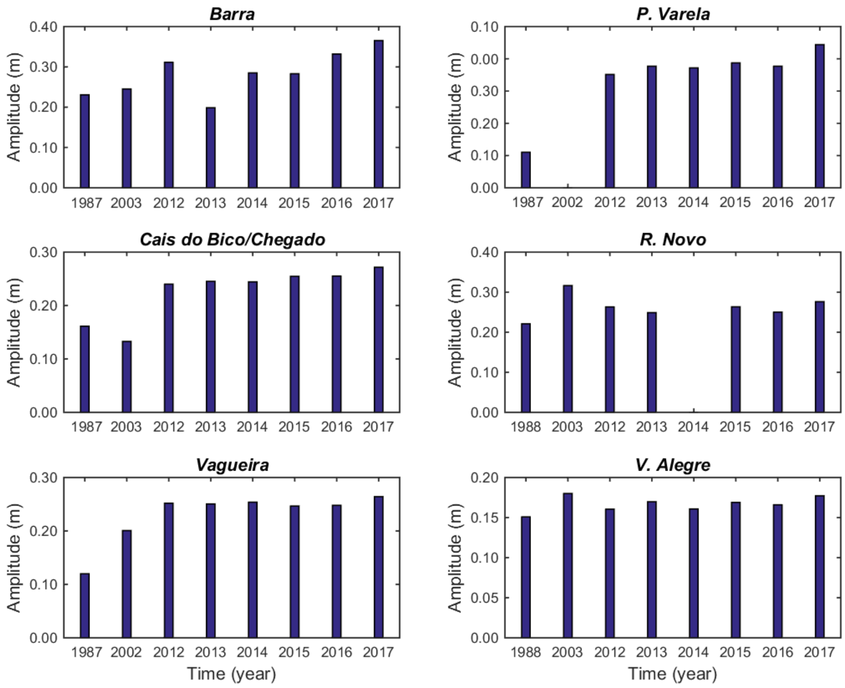


Figure 7 – Amplitude of tidal constituent S_2 in all tide gauges, from 1987/88 to 2017.

As for the tidal constituent M_2, is also found to have had a significant increase in amplitude of the S_2 constituent in most of the tide gauges from 1987/88 to 2002/03 (Figure 7), apart from Cais do Bico/ Chegado, where was a decrease between 1987 to 2003. In the period from 2012 to 2017, the values practically did not change in Ponte Varela, Cais do Bico/Chegado, Vagueira and Vista Alegre.

From 1987/88 to 2002/03, the amplitude increased 9.53 cm in Rio Novo, 8.08 cm in Vagueira, 2.90 cm in Cais do Bico/ Chegado and Vista Alegre and 1.47 cm in Barra.

b) Phase

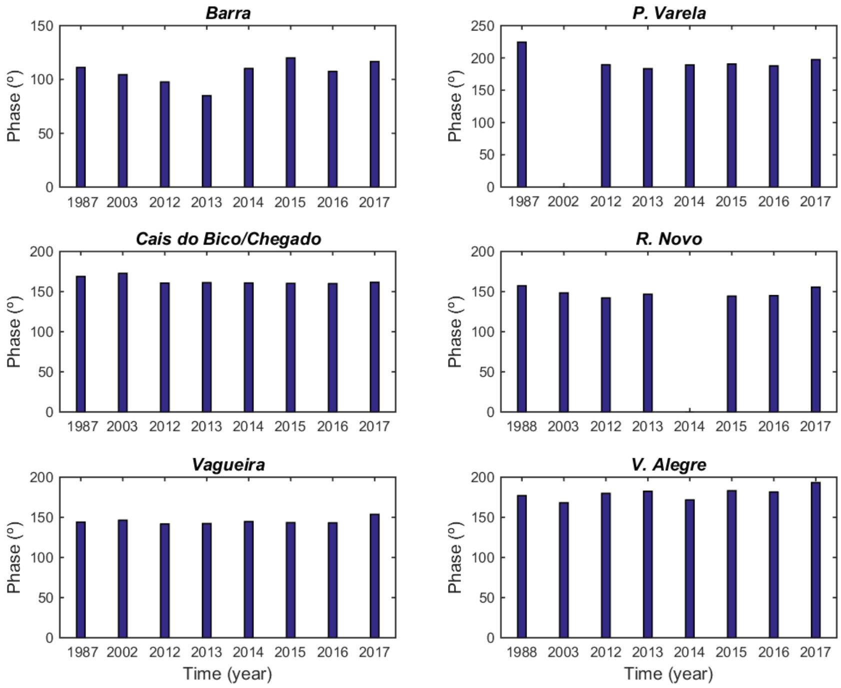


Figure 8 - Phase of tidal constituent S_2 in all tide gauges, from 1987/88 to 2017.

Concerning the phase (Figure 8), from 1987/88 to 2002/03 the semidiurnal solar constituent decreased in Barra, Rio Novo, Vista Alegre and in Ponte Varela. Featuring a slight increase in Cais do Bico/Chegado and Vagueira. For the time interval between 2002/03 and 2017, the phase does not change significantly.

The variations of the phase for this constituent are lower than for the constituent M_2, being approximately 8° (6.4 min) for Rio Novo, Vista Alegre and Barra. For Cais do Bico / Chegado and Vagueira the increase was 3° (2.4 min).

The harmonic analysis of the principal tidal constituents (lunar principal, M_2, and solar principal, S_2) is the most relevant for studies of tidal changes due to variations in the geomorphology of Ria de Aveiro, since the energy associated with the frequencies of these two constituents is the highest, as reported in the analysis of the Fourier spectra, and because their amplitude values are the highest in relation to the other constituents studied.

A general increase in the amplitude and a decrease in the phase for these constituents is a consequence of natural and anthropogenic modifications in the Ria de Aveiro. A dredging operation took place along the main channels of Ria de Aveiro in 1998. The increase in water depth appears to be the most important factor contributing to results found, since the highest variations occurred between 1987/88 and 2002/03.

The slight differences, both in the amplitude and the phase, of these constituents between 2002/03 and the following years, show that the north jetty extension by 200 m of the north jetty in 2012, did not cause great changes in the local dynamics of the tide, confirming the numerical modelling predictions by Dias and Mariano (2011).

5.1.2.3. Tidal constituents M_4 and M_6

a) Amplitude

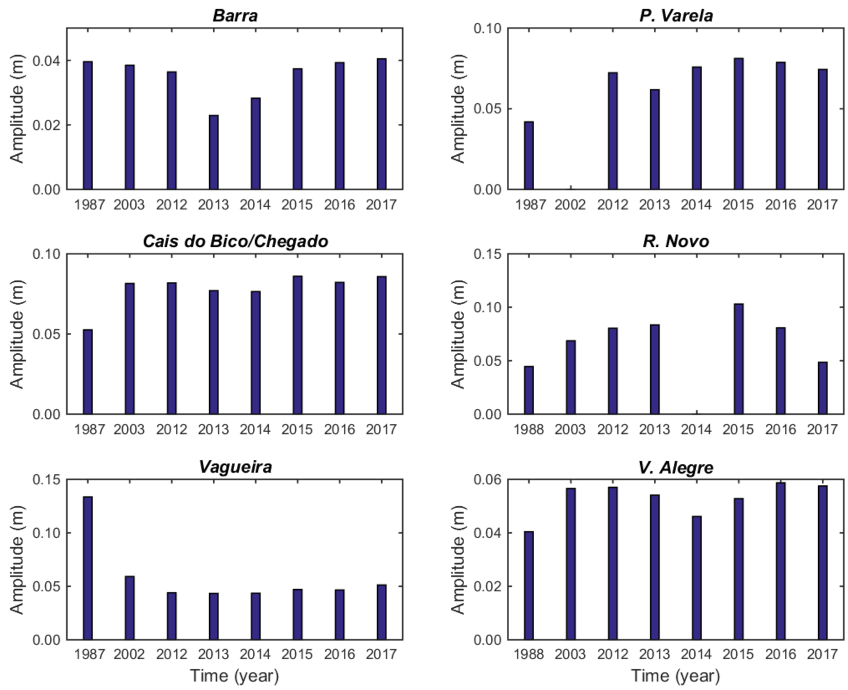


Figure 9 - Amplitude of tidal constituent M_4 in all tide gauges, from 1987/88 to 2017.

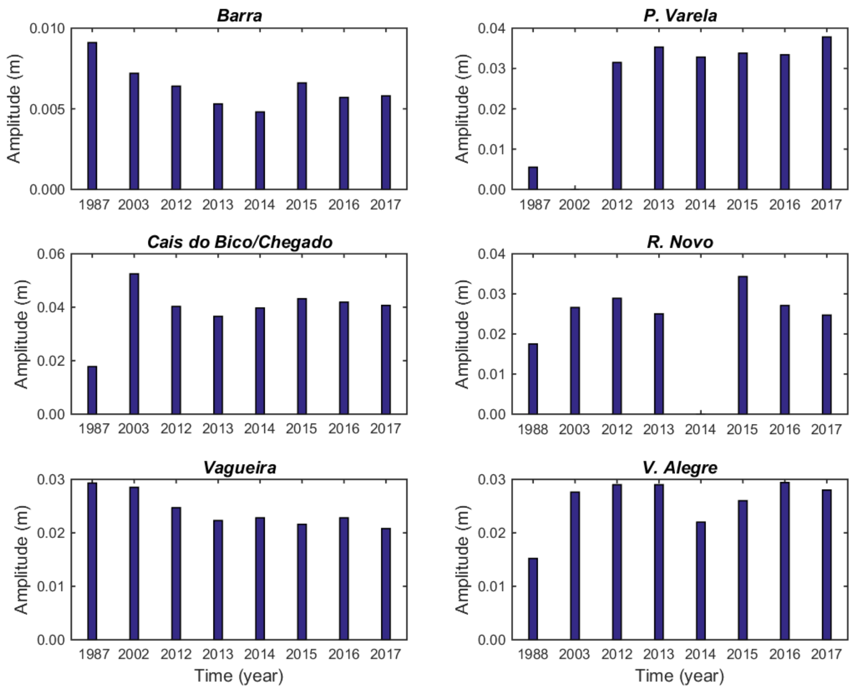


Figure 10 - Amplitude of tidal constituent M_6 in all tide gauges, from 1987/88 to 2017.

The shallow water tidal constituents, M_4 and M_6, exhibit the same behaviour for Ponte Varela, Cais do Bico/Chegado, Rio Novo and Vista Alegre. There was an increase in tidal amplitude from 1987/88 to 2002/03 in these tide gauges and a decrease in Barra and Vagueira (Figures 9 and 10).

From 1987/88 to 2002/03, the highest amplitude difference was recorded at Cais do Bico/Chegado for both M_4 (2.89 cm) and M_6 (3.47 cm). Vista Alegre presented the lowest value for M_4 (1.62 cm) and Rio Novo for M_6, 0.91 cm. In Vagueira and Barra, there was a decrease from 1987/88 to 2002/03, which for M_4 was in the order of 8.95 cm and 0.30 cm, and for M_6 of 0.46 cm and 0.27 cm, respectively.

In general, the amplitude of M_4 and M_6 increases with the increase of M_2. This trend is justified by the transfer of part of the energy from M_2 to the constituents M_4 and M_6. Despite this trend, there was a decrease in the amplitude of these two constituents in Barra and Vagueira. This can be justified by a reduction of the bottom friction due to the increase of the channel depth from Barra to Vagueira and specifically in the area where the tide gauges are located, a result of the dredging throughout the lagoon in 1998.

As for the constituents previously studied, between 2012 and 2017 the amplitude did not change significantly, except for Rio Novo, which values varied but without any trend. This station is influenced by the Vouga river, which represents the main source of freshwater to the lagoon. The increase of the flow in certain months of the year can change the values of these two constituents, since they are directly dependent on the bottom friction, which is related to the increase of depth.

b) Phase

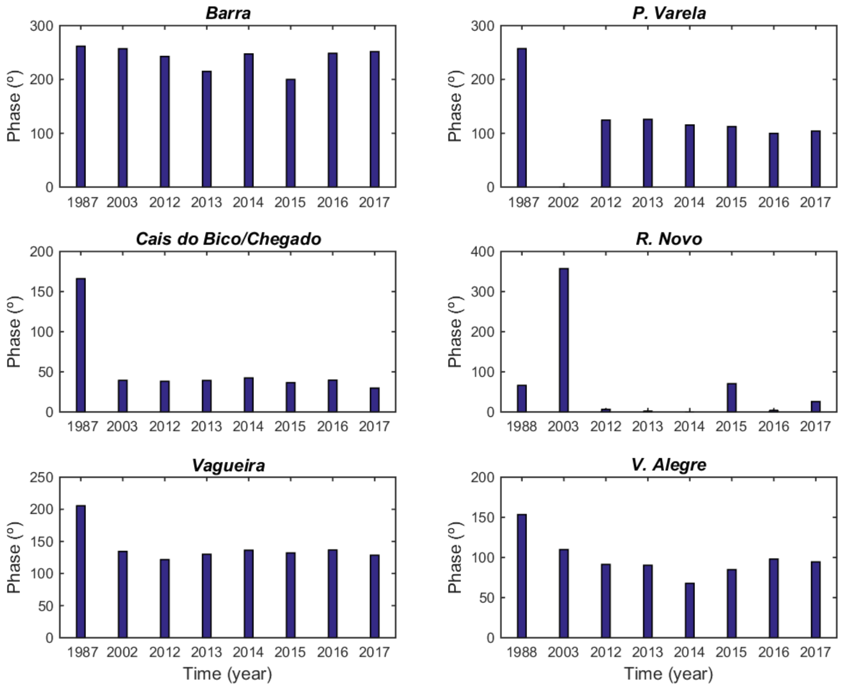


Figure 11 - Phase of tidal constituent M_4 in all tide gauges, from 1987/88 to 2017.

Regarding the phase, for the constituents M_4, from 1987/88 to 2002/03 the phase decreased, except for Rio Novo, with the lowest decrease occurring in Cais do Bico/Chegado, 126.77° (131.2 min) (Figure 11). For the other stations, the decrease was as follows: 71.19° (73.70 min) for Vagueira, 43.62° (45.15 min) for Vista Alegre and 4.59° (4.75 min) for Barra. As for the constituents previously studied, between 2012 and 2017 the amplitude did not change significantly, except for Rio Novo, which values varied without any trend. The same pattern was found, for this station, for the constituent M_6 (Figure 12).

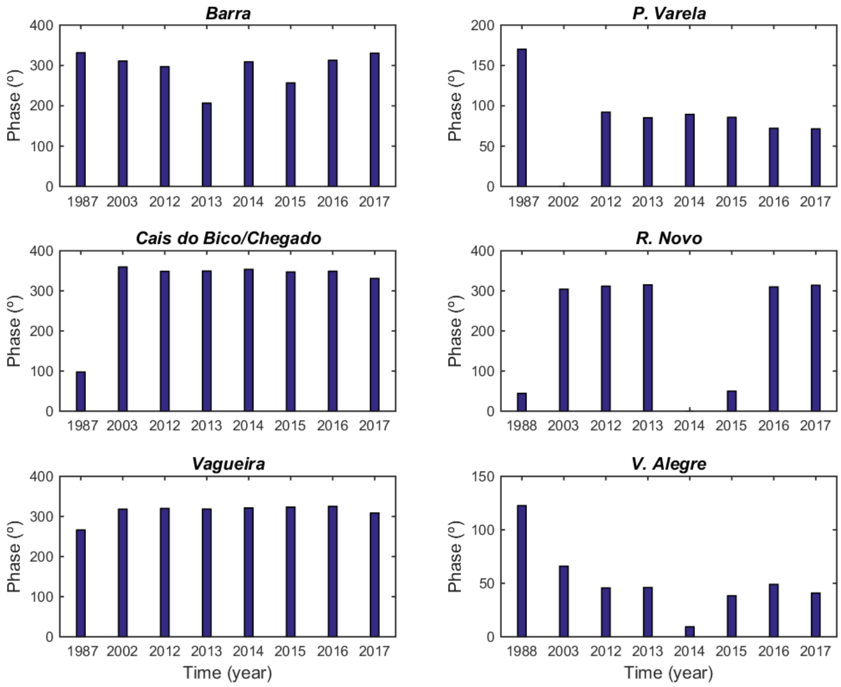


Figure 12 - Phase of tidal constituent M_6 in all tide gauges, from 1987/88 to 2017.

For the constituent M_6, from 1987/88 to 2002/03, the phase increased in the Cais do Bico/Chegado (262.66° which corresponds to 181.24 min), Vagueira (51.80° which corresponds to35.74 min) and Rio Novo (259.64° which corresponds to 177.78 min), and decreased in the other stations. Between 2012 and 2017 the phase did not change significantly, except for Rio Novo in 2015, and for Vista Alegre in 2014. This different behaviour may have occurred because during these years measurement anomalies occurred, which may have influenced the results obtained, as previously mentioned in methodology section.

5.1.2.5. Tidal constituent MSf – Amplitude and Phase

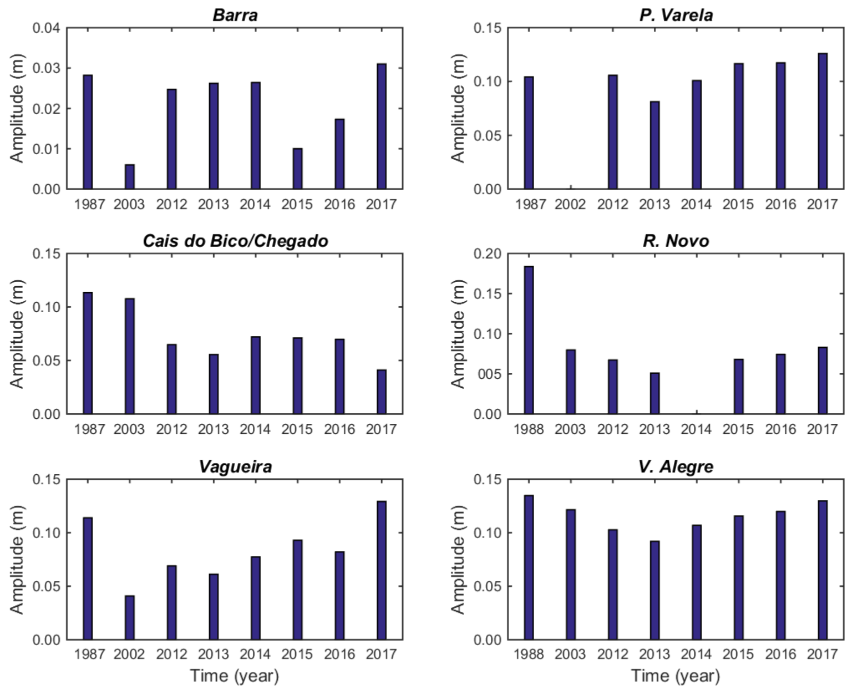


Figure 13 - Amplitude of tidal constituent MSf in all tide gauges, from 1987/88 to 2017.

The tidal constituent MSf, represents the variation of the water level in a spring / neap tide cycle, results from the interaction between M_2 and S_2.

According to Figure 13, a decrease in amplitude from 1987/88 to 2002/03 can be observed in most stations. The amplitude decreased 10.39 cm in Rio Novo, 7.30 cm in Vagueira, 1.33 cm in Vista Alegre, 0.57 cm in Cais do Bico/ Chegado and 1.37 cm in Barra. Between 2012 and 2017, there is a trend towards the increase of amplitude of this constituent in most stations, although in some intermediate years an opposite trend is found in Barra and Cais do Bico/Chegado. This means that, in this last time interval, the amplitude difference between spring and neap tides has been increasing.

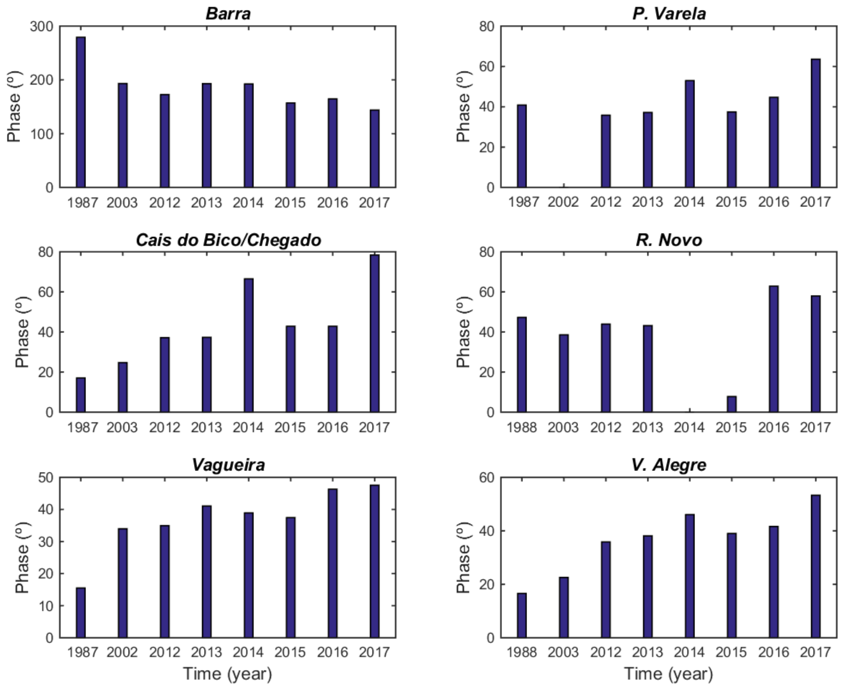


Figure 14 - Phase of tidal constituent MSf in all tide gauges, from 1987/88 to 2017.

According to Figure 14, there is a phase increase of MSf constituent in the stations Cais do Bico/Chegado (4.66° which corresponds to 4.58 hours), Vagueira (18.45° which corresponds to 18.15 hours) e Vista Alegre (5.97° which corresponds to 7.00 hours), and a decrease in Rio Novo (8.69° which corresponds to 8.55 hours) and Barra (20.86° which corresponds to 20.53 hours), from 1987/88 to 2002/03. In the following years, there is a general trend towards the increase of the phase, although in some intermediate years an opposite trend is found.

5.2. Form Factor

In Table 2 is presented the form factor determined for the different stations studied between 1987/88 and 2017. The Form number was determined by expression 4.1.

Table 2 – Form Factor values between 1987/88 to 2017.

Station /Year	1987/88	2002/03	2012	2013	2014	2015	2016	2017
Barra	0.104	0.106	0.060	0.067	0.063	0.092	0.091	0.080
P. Varela	0.160	-	0.114	0.106	0.113	0.111	0.104	0.123
Chegado	0.117	0.112	0.102	0.098	0.104	0.101	0.101	0.060
Rio Novo	0.088	0.071	0.098	0.100	-	0.101	0.103	0.092
Vagueira	0.163	0.117	0.104	0.104	0.108	0.106	0.106	0.098
V. Alegre	0.126	0.123	0.126	0.121	0.141	0.111	0.124	0.108

The values of F obtained along these years did not vary significantly. The results show that the tide is predominantly semidiurnal in Ria de Aveiro. There are two high tides and two low tides in a period of 12h and 25 minutes, which corresponds to a half of a lunar day.

5.3. Tidal Asymmetry

The relative phase φ_{M4} , was determined for each of the stations from 1987/88 to 2017, applying the mathematical expression 4.2.

Table 3 – Relative phase φ_{M4}, in degrees, between 1987/88 and 2017.

Station /Year	1987/88	2002/03	2012	2013	2014	2015	2016	2017
	φ_{M4}	φ_{M4}	φ_{M4}	φ_{M4}	φ_{M4}	φ_{M4}	φ_{M4}	φ_{M4}
Barra	256.31	259.92	264.52	265.00	289.23	229.94	269.40	265.30
P. Varela	81.61	-	153.68	145.14	161.22	163.72	165.95	162.91
Chegado	110.58	201.01	199.31	198.54	195.34	197.86	195.95	198.39
Rio Novo	169.45	195.50	208.43	214.43	-	212.71	213.10	188.39
Vagueira	52.89	76.32	90.13	80.71	73.73	80.73	75.00	79.52
V.Alegre	137.12	158.18	173.33	176.90	174.10	174.22	170.97	172.12

The results (Table 3) show that all stations located in the channels of the lagoon are flood-dominating in 1987/88, as already mentioned by Araújo *et al* (2008).

From this date onward, it can observe that while the Ponte Varela, Vagueira and Vista Alegre stations still remain flood-dominant, which means that the maximum velocity during the flood is higher than during the ebb and thus the sediment transport is done upstream, the Rio Novo and Chegado stations show ebb dominance, which translates in higher velocity during the ebb rather than the flood, and as such the sediment transport is preferentially done downstream which increases the erosion in those places.

The mouth of the lagoon is ebb-dominant between 1987/88 and 2017.

5.4. Meteorological Tides

The total number of events where the residual value is higher than three times the standard deviation, 3σ, or less than -3σ, is represented in Table 4, as well as their duration.

Table 4 – Frequency of extreme surge events at the different tide gauges in terms of the local standard deviations of the residuals, from 2012 to 2017.

Tide gauge	**Duration (h)**	**Events less than -3σ**	**Events greater than 3σ**
Ponte Varela	1-4	223	323
	5+	2	11
Chegado	1-4	63	89
	5+	-	4
Rio Novo	1-4	266	121
	5+	-	4
Vagueira	1-4	250	207
	5+	-	4
Vista Alegre	1-4	197	180
	5+	2	4

For the identification of meteorological tide events, it was not only considered the situations in which the residual values were higher than three times the standard deviation (3σ), or lower than -3σ, but additionally their duration (Table 4). Also, to know and understand the relationship between meteorological variables and the generation of residual elevations, graphs of the atmospheric pressure, wind intensity and direction, precipitation and water level and residual were performed.

A selection of the obtained events was made to distinguish those that were generated by the variations of atmospheric pressure and the wind intensity, and those that were formed due to other effects, namely the occurrence of spring tides. From the different events, a separation between the remotely generated and the locally generated events was also performed.

From the different events occurring between 2012 and 2017, where residual values were higher than three times the standard deviation of the annual residuals (positive anomalies), only two influenced the entire lagoon (January and December 2013), having been generated by adverse meteorological conditions verified at national level. The remainder were manifested only locally in October 2012, March 2013, September 2015 and May 2016.

The events with negative anomalies occurred in a smaller number, emphasizing only that they occurred in February and March of 2015.

5.4.1. Analysis of Positive Anomalies

During the year 2013, positive anomalies were recorded in all the stations under study in January and December. In October 2012, March 2013, September 2015 and May 2016 were only verified local events.

January 2013

Between January 18th and 19th, 2013, Portugal mainland was affected by extreme weather conditions. This severe weather, caused by the storm called Gong Storm, affected mainly the centre and south of Portugal mainland. The rapid drop in pressure caused wind speed to rise, reaching the maximum of "Force 12" on Beaufort scale (0 to 12) in some locations (wind speed between 25 ms^{-1} and 33 ms^{-1}), accompanied by heavy rain (Liberato, 2014).

Due to the weather conditions generated by this storm, the water level and the residual values (higher than three times the standard deviation for this month) were recorded on 19 and 20 January (Figures 15 and 16).

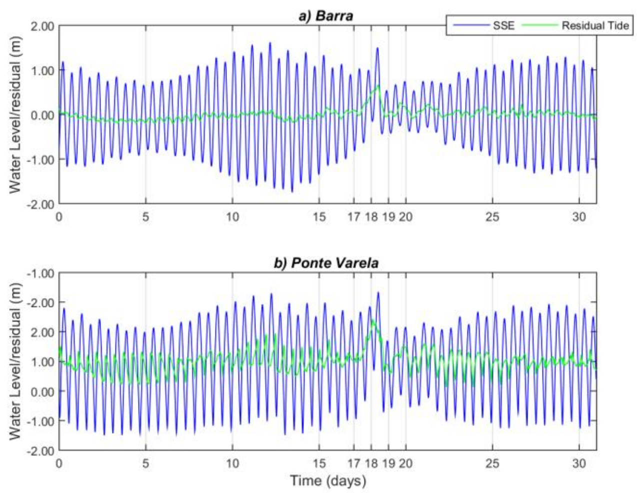


Figure 15 - Observed water level (m) and residual levels (m) in January 2013, in the stations:

a) Barra; b) Ponte Varela;

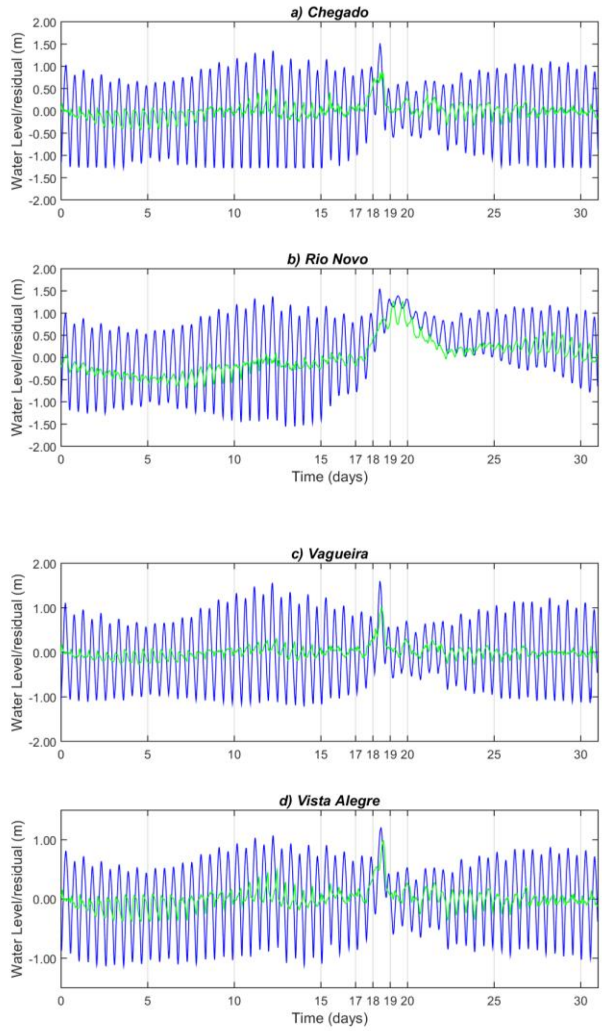


Figure 16 –Observed water level (m) and residual levels (m) in January 2013, in the stations: a) Chegado; b) Rio Novo; c) Vagueira and d) Vista Alegre.

In Rio Novo, the highest SSE and residual values recorded were 4.04 m and 1.26 m, respectively. The duration of this event in this area was approximately 31 hours between 19 and 20 January. In other stations, the storm occurred mainly between January 18 and 19, with the highest SSE values of 3.90 m and the residual of 1.00 m in Vagueira, and in this area, the effect of the storm was felt for 13 hours. In Vista Alegre, the value that was recorded for the water level was 3.92 m and for the residual of 0.98 m, the duration of the event was 10 hours. In the case of Ponte Varela, Chegado and Barra, the duration of the storm was 18 hours, with SSE values being: 3.55 m, 3.82 m and 3.80 m respectively, and for the residuals of 0.72 m, 0.87 m and 0.66 m.

One of the effects of the Gong Storm, which was mainly observed on the day 19^{th}, was the increase in water level in Ria de Aveiro, as well as in the residual values (Figures 15 and 16).

The large drop in atmospheric pressure, from 1005 hPa to a minimum pressure of 980 hPa 24 hours later (Figure 17), the increase of the wind intensity on that same date (Figure 18), that had a direction change from SW on day 18th to NW on the 19th [Figure 19 a) and b)] and the large precipitation (Figure 20), characterize this storm.

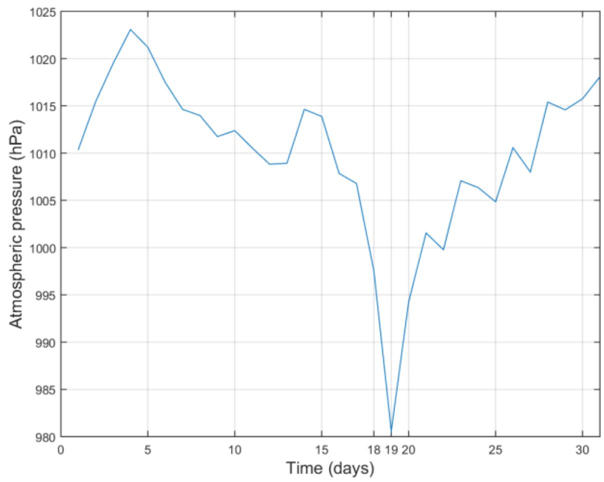


Figure 17 - Atmospheric pressure (hPa), January 2023.

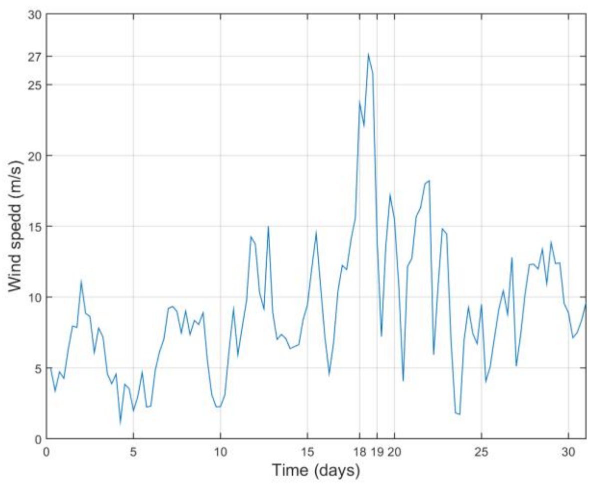


Figure 18 –Wind speed (m/s), January 2013

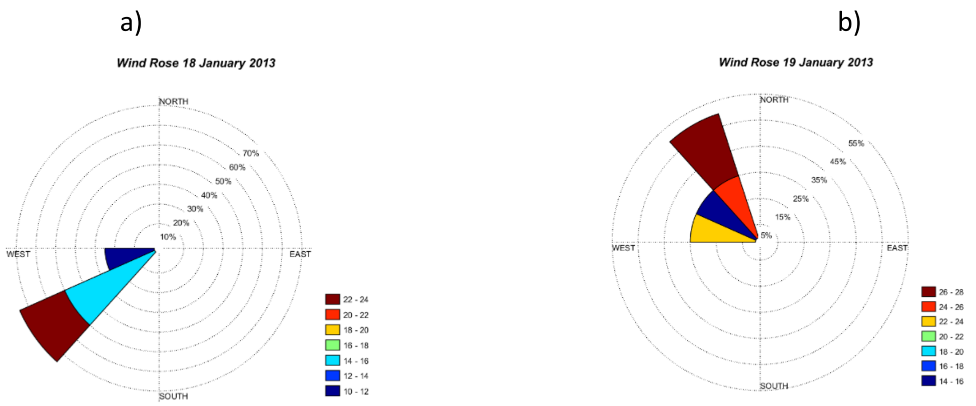


Figure 19 - Wind Roses in the days a) 18th and b) 19th January.

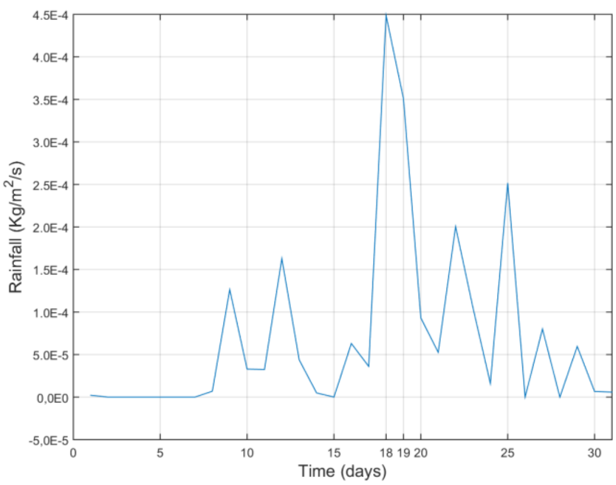


Figure 20 - Rainfall (Kg/m²/s²), January 2013.

From the mathematical expression 2.13, it is possible to determine the effect of the atmospheric pressure in the sea surface elevation. For this variation of pressure corresponds an increase of the SSE of about 35.00 cm. Considering the effect of wind, by equation 2.16, the SSE may increase by about 11.60 cm considering its effect along the lagoon channels. Another effect caused by the wind tension is the accumulation of water at the banks of the channels, especially in areas where the wind has perpendicular direction to the banks of the channels. Adding to these factors the high value of the precipitation, justifies the values obtained for the SSE and for the residuals. On average, the values found for SSE in all stations were 1.00 m higher than the annual average for each station.

December 2013

In December, between the 24th and 26th, all stations (except Rio Novo, the tide gauge was withdrawn on 24 October 2013), recorded meteorological tides (Figure 21).

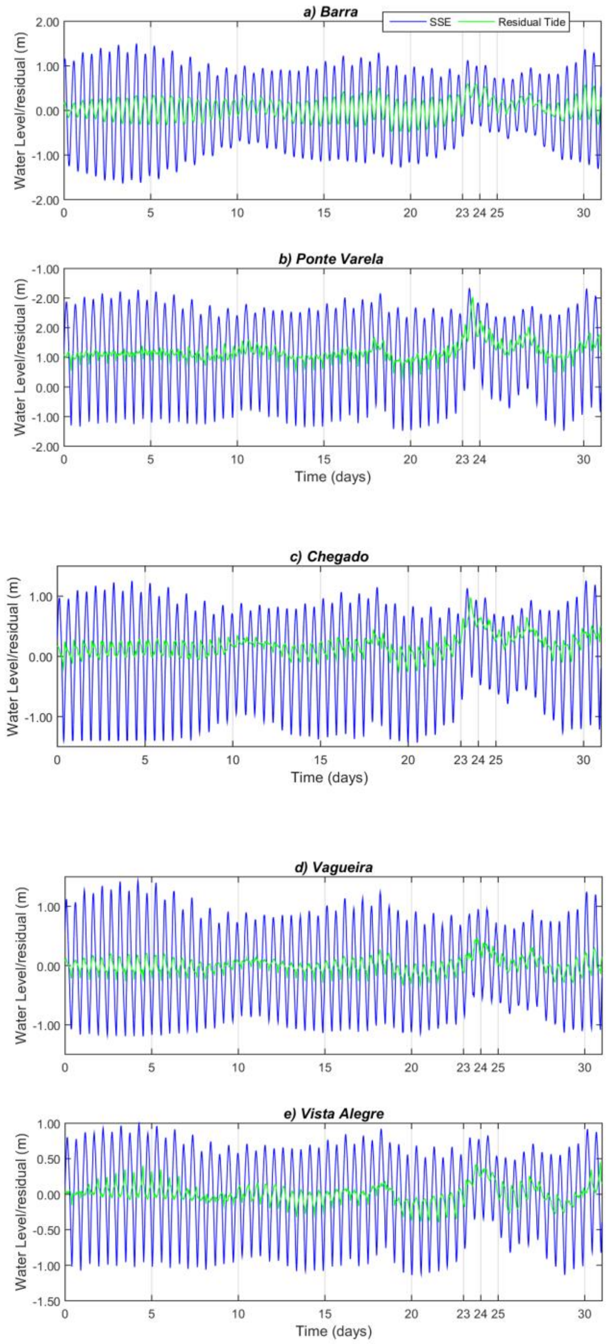


Figure 21 - Observed water level (m) and residual levels (m) in December 2013, in the stations:

a) Barra; b) Ponte Varela; c) Chegado; d) Vagueira and e) Vista Alegre.

In Chegado, the highest SSE and residual values were recorded, being 3.79 m and 0.98 m, respectively. The duration of this event in this area, in Ponte Varela and Barra was approximately 22 hours, between 24 and 25 December. In Barra the SSE value was 3.72 m and the residual value was 0.56 m. In Ponte Varela, the value of the SSE reached 3.47 m and the residual 1.02 m. In Vagueira, SSE values of 3.70 m and 0.48 m were recorded for the residuals, the storm lasted 6 hours. At Vista Alegre, SSE values of 3.41 m were found and for residual values of 0.45 m, with the storm lasting 12 hours.

Although there was an increase in water levels in these days (24^{th} and 25^{th} December), at all stations, Ponte Varela recorded the highest value between days 23 and 24, for this month. In the remaining tide gauges, the highest values of SSE were recorded at dates close to the New Moon – spring tides. In Vagueira and Vista Alegre on day 5 (New Moon was on the 3^{rd} day) and on Chegado was on day 31 (New Moon occurred on the 31^{st} day).

Once again, this event occurred due to the combination of different meteorological factors: a marked decrease in atmospheric pressure (below 1000 hPa) on day 24, Figure 22, an increase in wind intensity and duration, with predominant wind direction of W and SW, as it is shown in Figure 23 a) and b).

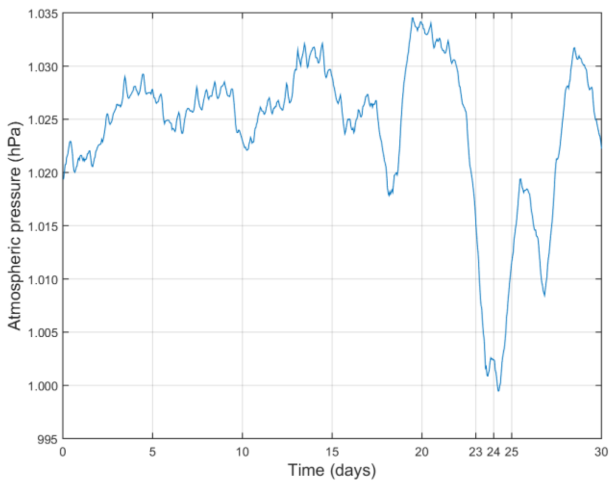


Figure 22 - Atmospheric pressure (hPa), December 2013.

a) b)

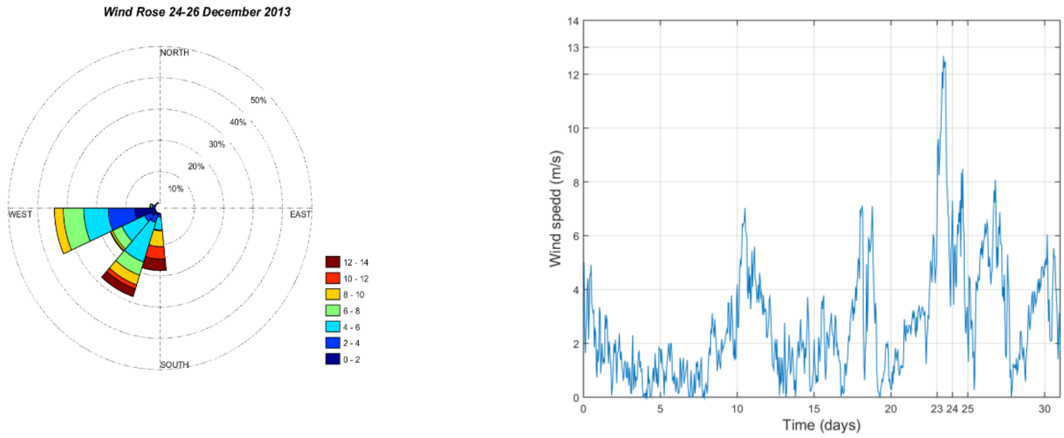


Figure 23 – a) Wind Rose in the days 24th to 26th December.

b) Wind speed (m/s), December 2013.

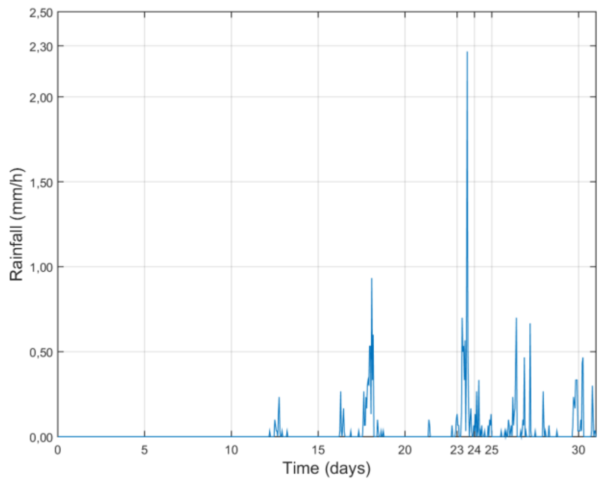


Figure 24 - Rainfall (mm/h), December 2013.

By theoretically calculating the values of the rise in water level due to the variation of the atmospheric pressure and the action of the wind, using the expressions 2.13 and 2.16, respectively, it can see that there are values in the order of 30.00 cm for the variation of the atmospheric pressure and 2.60 cm for the wind stress. It was verified that the duration of the wind action was high, more than 24 hours, with predominant W direction, the accumulation of water at the banks of the channels is a factor to be considered when determining the elevation of the water level, especially if the effect of the wind was felt perpendicularly to the margins of the channels than along the channels. Adding to these factors, justifies the values obtained for the SSE and for the residuals.

Local meteorological storm events

In October 2012, March 2013, September 2015 and May 2016 only local generated events of meteorological tides were found.

The Ponte Varela area was the region where most events took place. This may be related to local conditions, such as: the width of the channel, which is the largest when compared to the rest of the lagoon, with an unobstructed distance over which the wind can blow in a certain direction, increasing the size of the water slope on one side of the channel. The mathematical equation 2.17, also shows that the smaller the depth of the site, the higher the slope; also, the surrounding area is more unprotected, and the absence of high vegetation and/or housing, or other infrastructure, makes Ponte Varela a place where wind effects are most felt.

October 2012

From the analysis of Figure 25, it was verified that during October 2012 a meteorological tide occurred in Ponte Varela.

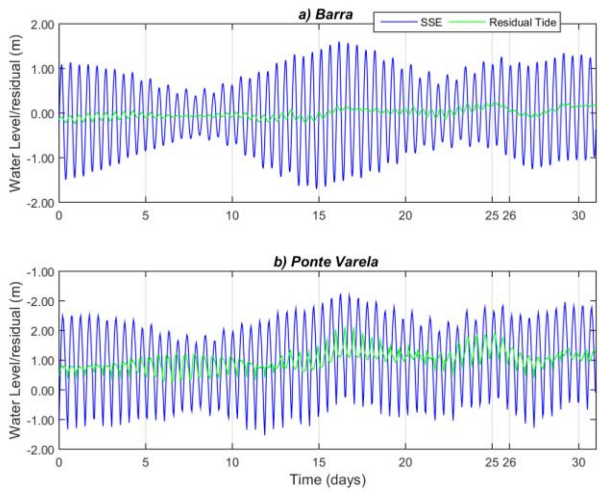


Figure 25 - Observed water level (m) and residual levels (m) in: a) Barra and b) Ponte Varela: October 2012.

One event was recorded between days 25 and 26 lasting 10 hours. The maximum value of the SSE was 3.36 m and the residual value was 0.55 m, on the 26th. In Barra meteorological tides did not occur during this month.

A decrease of the atmospheric pressure below 1000 hPa, occurred between the days 25 and 26 (Figure 26). The intensity and duration of the wind, on days 27 to 28 (Figure 28), was high, with predominant direction of ESE on day 25 and NW on day 26 [Figure 27 a) and b)].

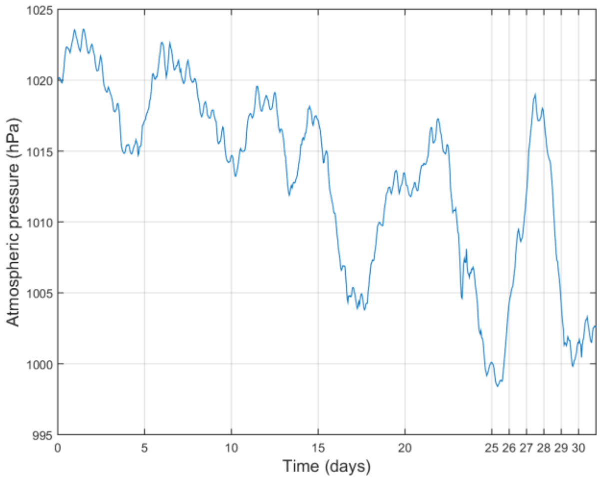
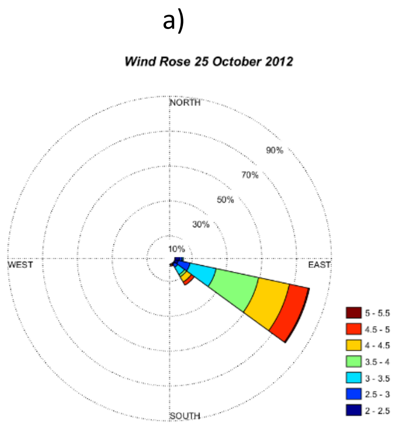


Figure 26 – Atmospheric pressure (hPa), October 2012.



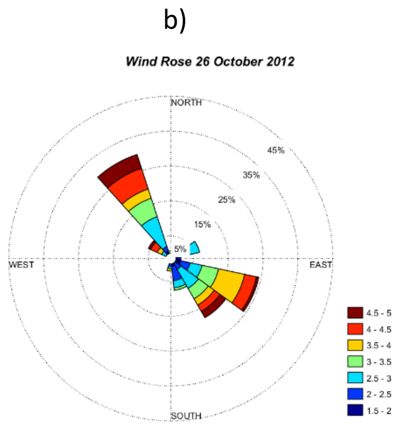


Figure 27 - a) Wind Rose in the days: a) 25th and b) 26th of October;

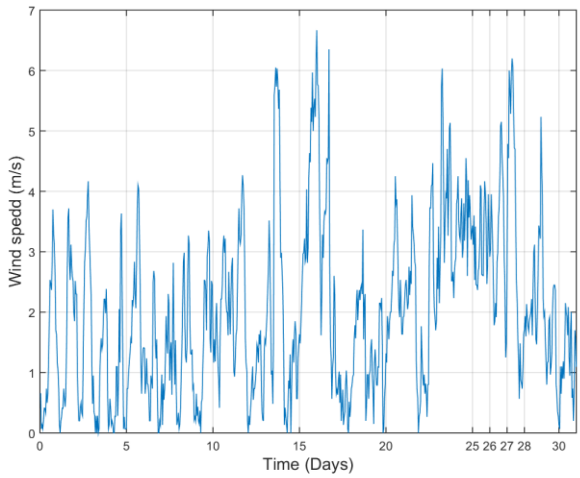


Figure 28 - Wind speed (m/s), October 2012.

With this variation in atmospheric pressure, and wind intensity, using the mathematical expressions 2.13 and 2.16, it is possible to verify that theoretically there was an increase in the water level of 20.00 cm due to the variation of the atmospheric pressure, but in relation to the wind the theoretical value is negligible since the intensity of the wind was not high. As the predominant ESE and NW wind, the water accumulation at the margin in this area of the lagoon was probably responsible for the values found for SSE and for the residuals.

Between the days 24 and 25 values of precipitation ranged between 0.50 mmh^{-1} to 0.80 mmh^{-1} (Figure 29). The influence of precipitation could have been felt locally, but the main meteorological factors for the formation of this event were the variation of the pressure and the wind intensity and duration.

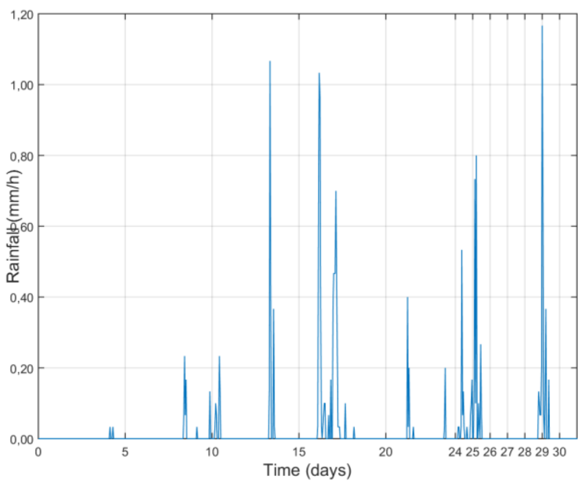


Figure 29 – Rainfall (mm/h), October 2012.

March 2013

In March 2013, there were values of positive anomalies lasting more than 5 consecutive hours for Ponte Varela and Chegado stations (Figure 30).

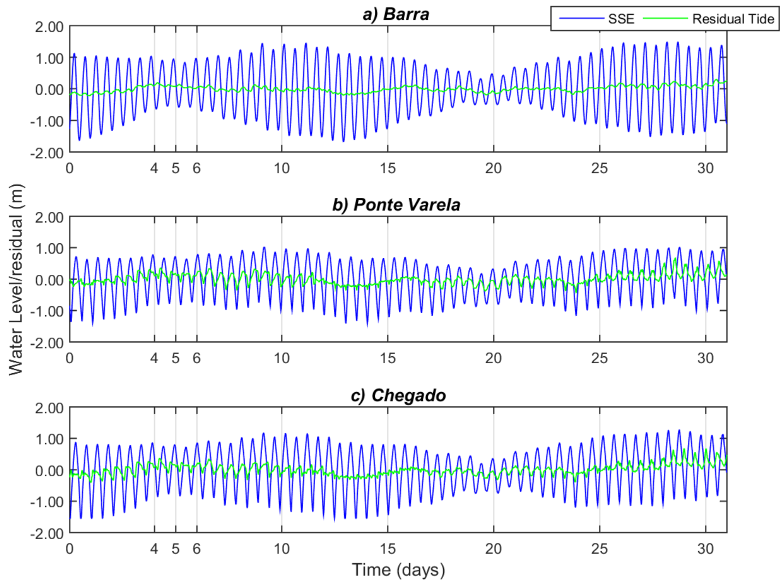


Figure 30 - Observed water level (m) and residual levels (m) in March in the stations:

a) Barra; b) Ponte Varela and c) Chegado.

The highest SSE and residual values were recorded in Chegado (3.85 m and 0.69 m, respectively). The duration of this event in this area was approximately 11 hours, between 5 and 6 March. In Ponte Varela the SSE value was 3.60 m and the residual value was 0.68 m, the storm lasted 18 hours in the same days. In Barra meteorological tides did not occur during this month.

In this month, the highest SSE in Ponte Varela and Chegado was recorded at the time of spring tides (New Moon on March 11th and Full Moon on March 27th). In Ponte Varela, on day 10, a value of 3.60 m and in Chegado on day 29, a value of 3.85 m was registered.

A decrease in atmospheric pressure between days 3 and 5, below the 990 hPa (Figure 31) and the values for the wind intensity and especially its duration, also between days 6 and 7 (close to 11 ms^{-1}) [figure 32 b)], were the meteorological conditions for the occurrence of meteorological tide events on March 4th and 10th.

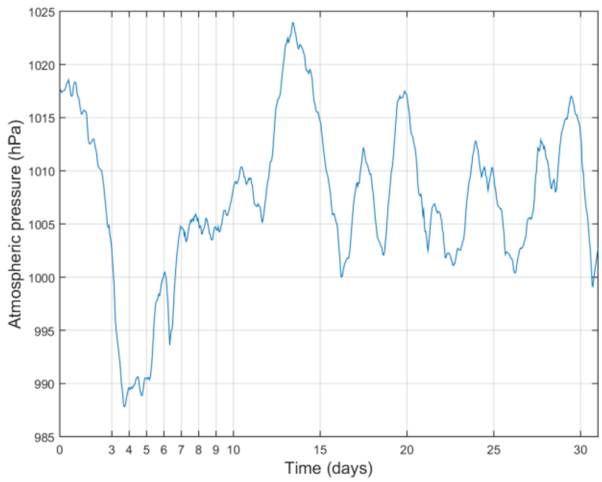


Figure 31 - Atmospheric pressure (hPa), March 2013.

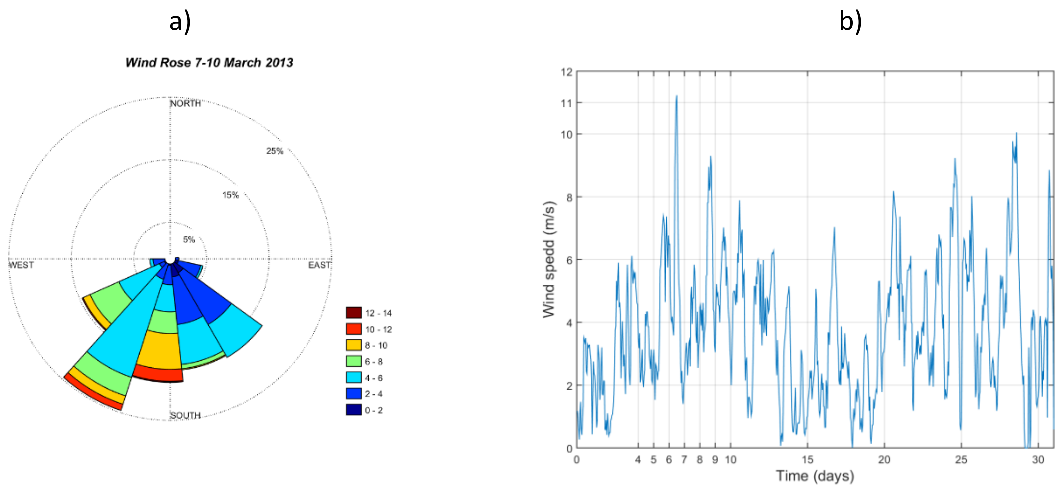


Figure 32 – a) Wind Rose in the days 7th to 10th March.

b) Wind speed (m/s), March 2013.

Theoretically calculating the values of the rise of the SSE due to the variation of the atmospheric pressure and the action of the wind, by the expressions 2.13 and 2.16, respectively, there are values in the order of 30.00 cm for the variation of the atmospheric pressure and 1.90 cm for the wind stress. It was verified that the duration of the wind action was high, more than 24 hours, with predominant SW direction, and the accumulation of water at the banks of the channels is a factor to be considered. All these factors together, justifies the values obtained for the SSE and for the residuals.

Precipitation values during 7th day (1.60 mmh^{-1}) (Figure 33), may have influenced locally.

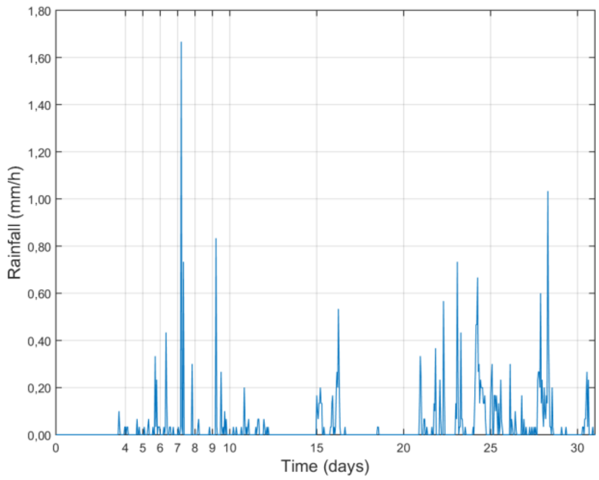


Figure 33 - Rainfall (mm/h), March 2013.

September 2015

From the analysis of Figure 34, it was verified that between 15 and 16 September a meteorological tide occurred in Ponte Varela and Rio Novo.

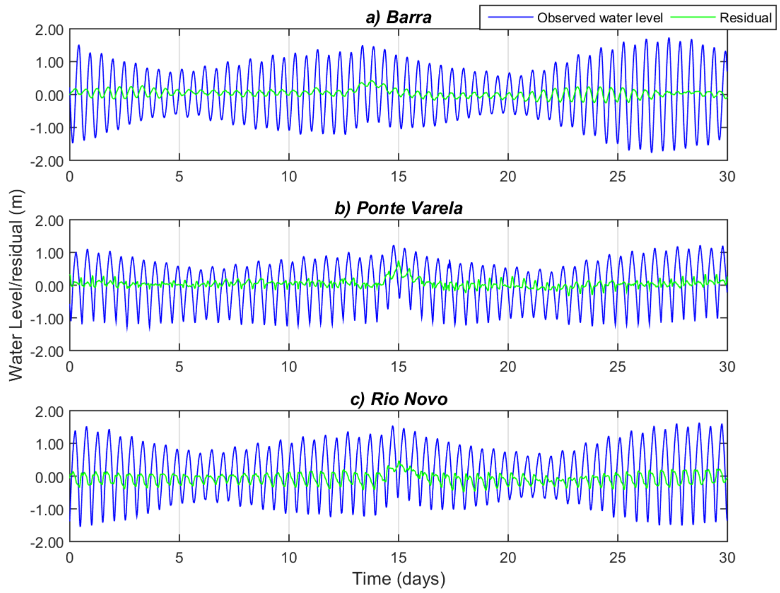


Figure 34 - Observed water level (m) and residual levels (m) in September in the stations: a) Barra; b) Ponte Varela and c) Rio Novo.

In Rio Novo, SSE and residual values were 3.93 m and 0.46 m, respectively. The duration of this event in this area was approximately 6 hours, between 15 and 16 September. In Ponte Varela the SSE value was 3.62 m and the residual value was 0.75 m, the storm lasted 15 hours in the same days. Although Barra did not verify residual values superior by 3σ, there was an increase of that values on September 15th (Figure 34).

During the days 15 and 16, there was a conjugation between high changes in atmospheric pressure (Figure 35), in which it dropped to values below 1000 hPa (a decrease of approximately 20 hPa in 24 hours) and an increase of the wind intensity [Figure 36 b)], reaching values in the order of 18 ms^{-1}.

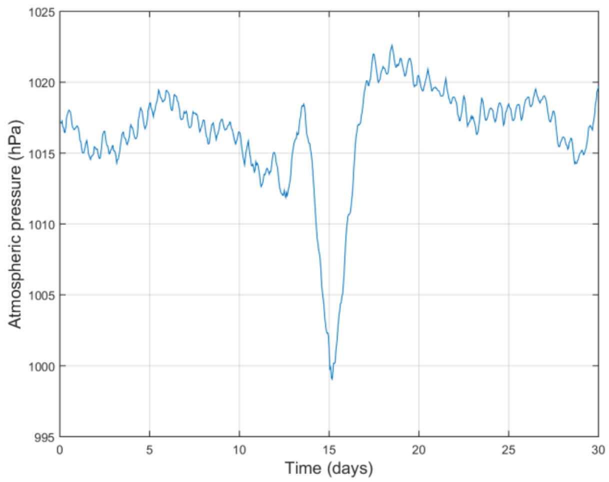


Figure 35 - Atmospheric pressure (hPa), September 2015.

a) b)

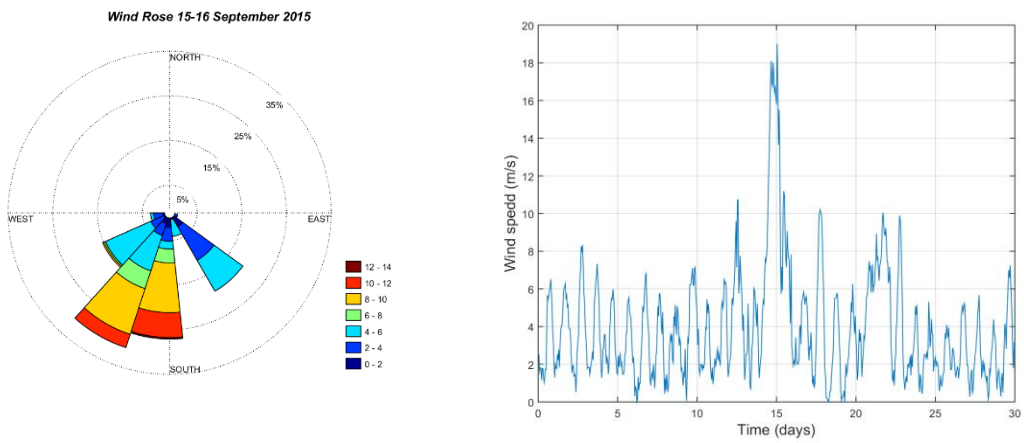


Figure 36 - a) Wind Rose in the days 15th to 16th September 2015.

b) Wind speed (m/s), September 2015.

With this variation in atmospheric pressure, and wind intensity, using the mathematical expressions 2.13 and 2.16, it is possible to verify that theoretically there was an increase in the water level of 20.00 cm due to the variation of the atmospheric pressure, and 6.40 cm for the wind stress. Another effect caused by the wind tension is the accumulation of water at the banks of the channels.

Precipitation had a maximum value of 1.40 mmh^{-1}, on 15th September (Figure 37).

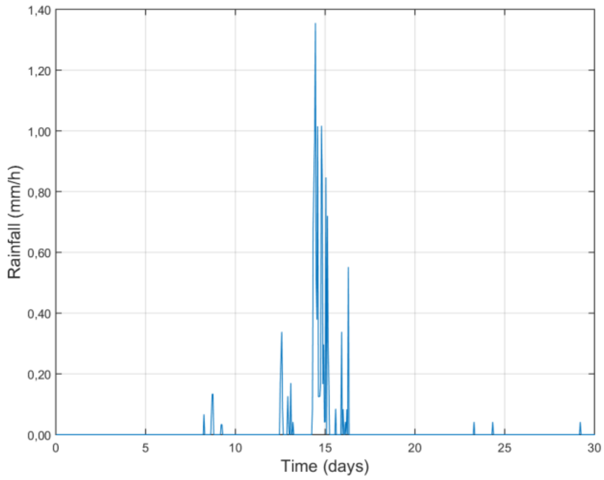


Figure 37 - Rainfall (mm/h), September 2015.

In Rio Novo a possible increase of the flow of Vouga River, due to the high precipitation, must also be considered.

Adding to these weather effects, spring tides were also recorded at that time, since New Moon was on 13th September, thus raising the water level.

May 2016

Positive anomalies were recorded in May 2016, in Ponte Varela, Chegado and Vista Alegre (Figure 38).

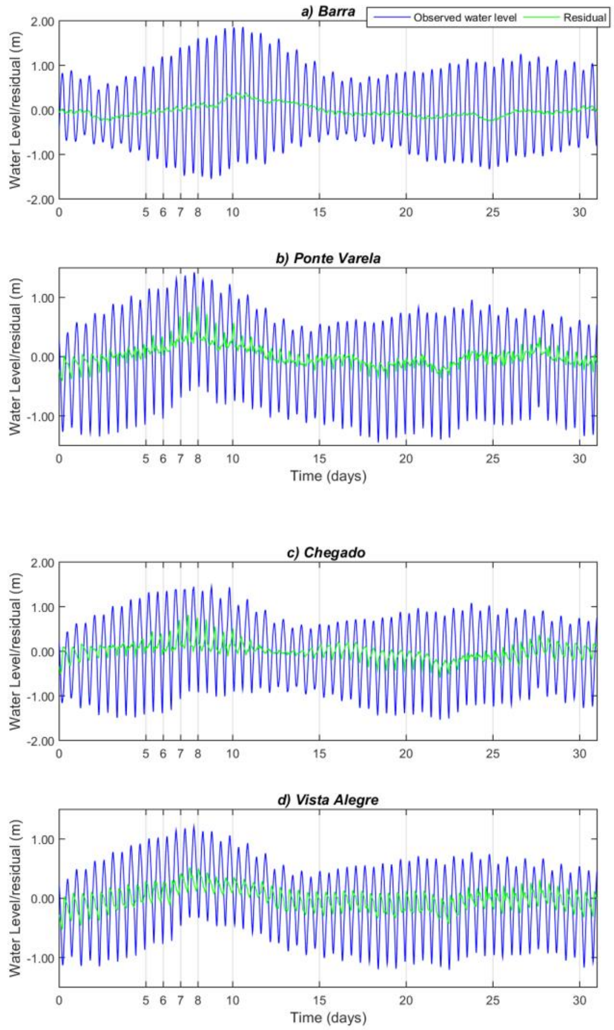


Figure 38 - Observed water level (m) and residual levels (m) in May 2016 in the stations: a) Barra; b) Ponte Varela; c) Chegado and d) Vista Alegre.

In Ponte Varela, the highest SSE and residual values were recorded, 3.86 m and 0.85 m, respectively. The duration of this event in this area was approximately 8 hours, at May 8th. In Chegado and Vista Alegre the storm lasted 5 hours in the same day and the SSE values were 3.85 m and 3.71 m, and the residual value were 0.81 m and 0.52 m, respectively. In Barra meteorological tides did not occur during this month.

The maximum annual SSE values found for the stations of Ponte Varela and Vista Alegre were recorded on May 8th, the day on which the storm effects were most felt. It should be noted that, although there are no residual values above 3σ with a duration of 5 hours or more in Rio Novo, the annual maximum value is recorded on this date.

New Moon on May 6th also influenced these values, due to spring tides.

A decrease in atmospheric pressure to 990 hPa between 7th and 8th May 2016 (Figure 39) and the increase of the wind intensity to 9 ms^{-1} on day 8 [Figure 40 b)], with predominant direction of E [Figure 40 a)], were the meteorological factors responsible for the formation of this event.

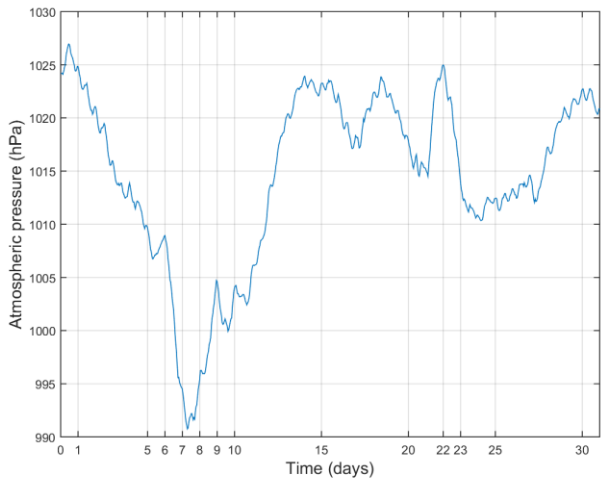
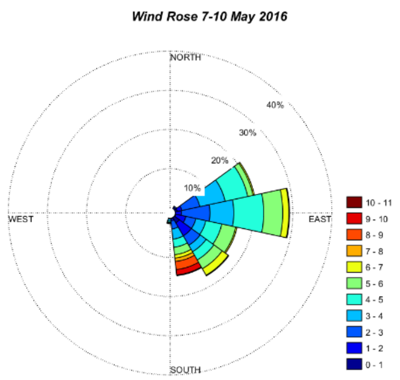


Figure 39 - Atmospheric pressure (hPa), May 2016.

a)



b)

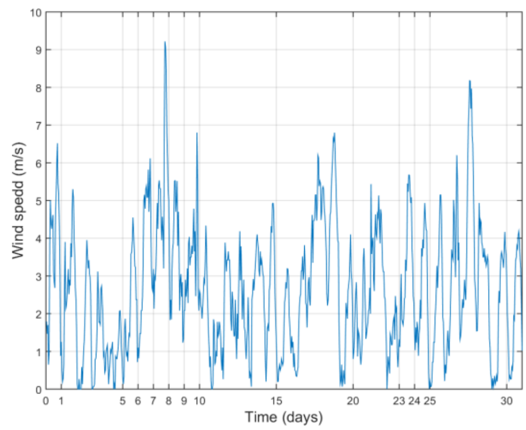


Figure 40 - Wind Rose in the days: a) 7th to 10th May;

b) Wind speed (m/s), May 2016.

Theoretically calculating the values of the rise of the SSE due to the variation of the atmospheric pressure and the action of the wind, by the expressions 2.13 and 2.16, respectively, there are values in the order of 20.00 cm for the variation of the atmospheric pressure and 1.30 cm for the wind stress. It was verified that the duration of the wind action was high, more than 24 hours and the accumulation of water at the banks of the channels is a factor to be considered when determining the elevation of the water level. Adding these factors, justifies the values obtained for the SSE and for the residuals.

Values close to the 2.00 mmh^{-1} for rainfall, also during day 8 (Figure 41), could have influenced the values of the residuals found in the stations of Ponte Varela, Chegado and Vista Alegre.

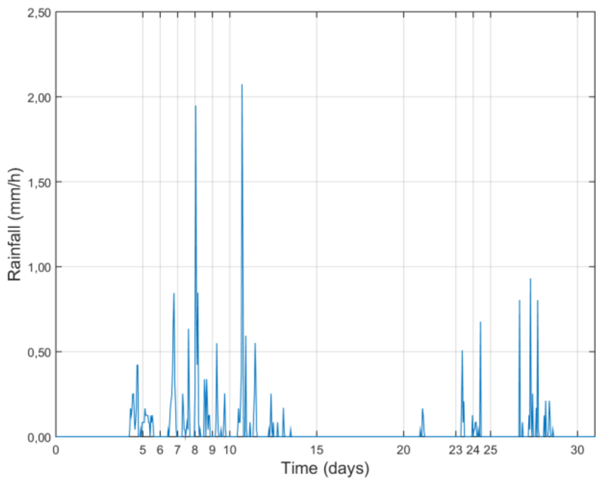


Figure 41 - Rainfall (mm/h), May 2016.

5.4.2. Analysis of Negative Anomalies

Negative anomalies were recorded only in Ponte Varela in the months of February and March 2015 (Figures 42 and 43) .

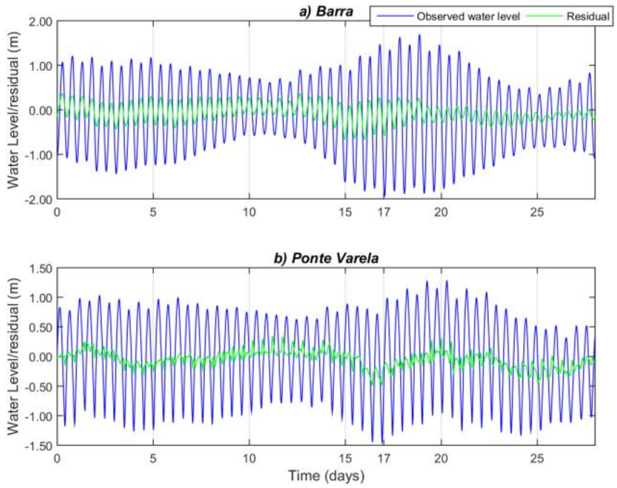


Figure 42 - Observed water level (m) and residual levels (m) in 1st to 28th February in: a)Barra and b) Ponte Varela.

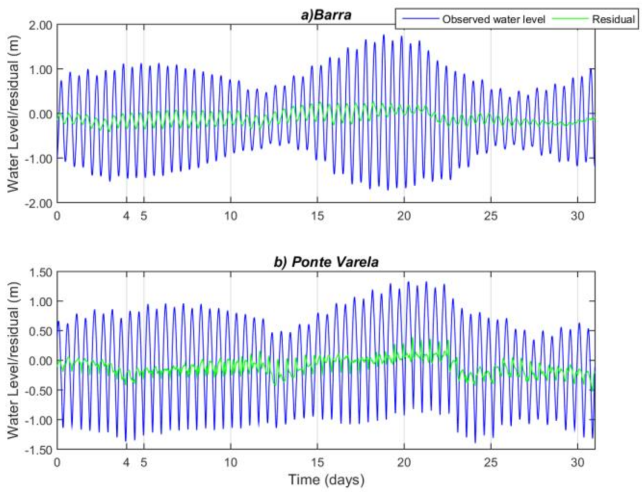


Figure 43 - Observed water level (m) and residual levels (m) in 1st to 31st March in:

a) Barra and b) Ponte Varela.

In Ponte Varela, the surface elevation (SSE) and residual values were 0.77 m and 0.49 m, in February 17th. The duration of this event in this area was approximately 12 hours.

In March, two events were recorded, the first between 4th and 5th March and the second between 28th and 31st March. The lowest SSE was in March 5th, 0.84 m, but the lowest residual value was -0.53 m in 31st de March. The storm lasted 7 hours between the 4th and 5th March, and 12 hours between the 28th and 31st March. In Barra meteorological tides did not occur during this month.

Spring tides occurred on February 18th and March 5th, and this may have influenced the occurrence of negative anomalies and the minimum values of water level found in these months.

In February, between days 16th and 17th, and in March between days 4th and 5th and between 28th and 31th, the atmospheric pressure rose to 1035 hPa (Figure 44 and Figure 45).

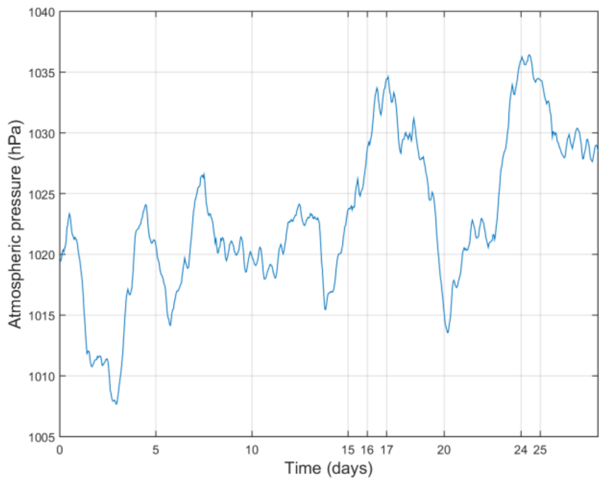


Figure 44 - Atmospheric pressure (hPa), February 2015.

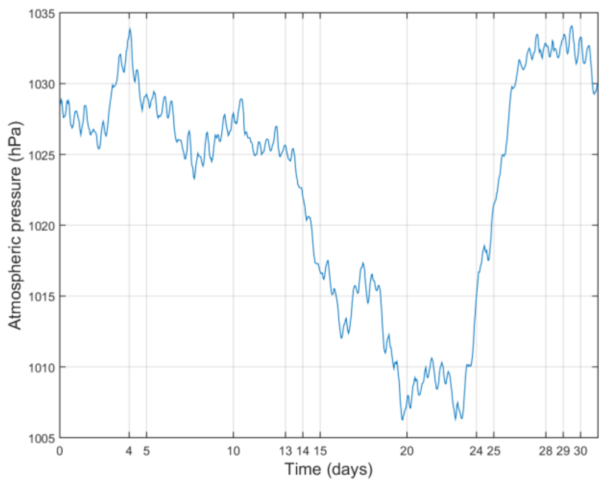


Figure 45 - Atmospheric pressure (hPa), March 2015.

As already mentioned, an increase in atmospheric pressure of one hPa will produce a theoretical decrease in sea water level of one centimetre (Pugh, 2004). At both time intervals recorded in February, the water level drop was around 15.00 cm, but in relation to March, the highest variation in atmospheric pressure was observed between days 28th and 31st, with a value of 30 hPa, corresponding to a drop-in water level of approximately 30 cm.

Regarding the wind intensity in February and March (Figures 46 and 48), ranged between 5 and 7 ms^{-1}, being the predominant NW direction in February and March 28th to 31st [Figure 47 and 49 b)]. At March 4th and 5th, the direction of the predominant wind was NE [Figure 49 a)].

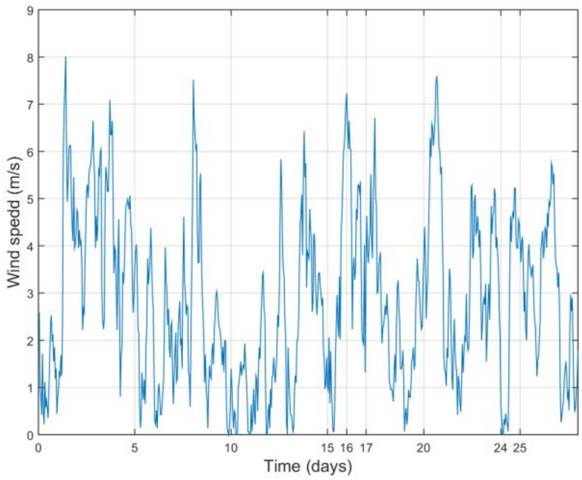


Figure 46 - Wind speed (m/s), February 2015.

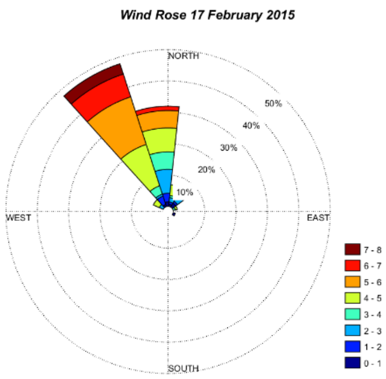


Figure 47 - Wind Rose in 17th February;

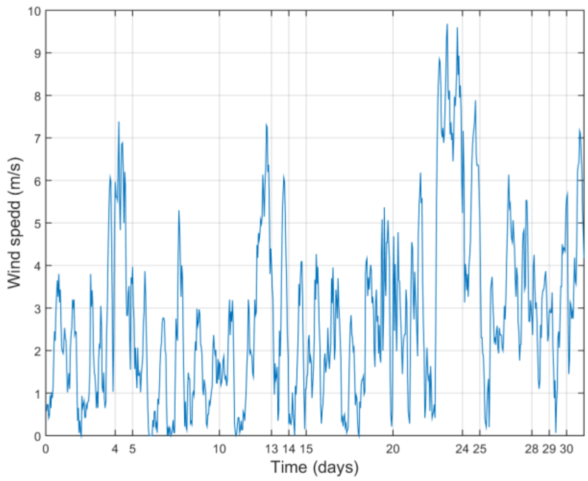
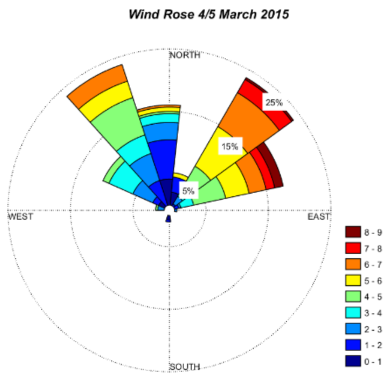


Figure 48 - Wind speed (m/s), March 2015.

a)



b)

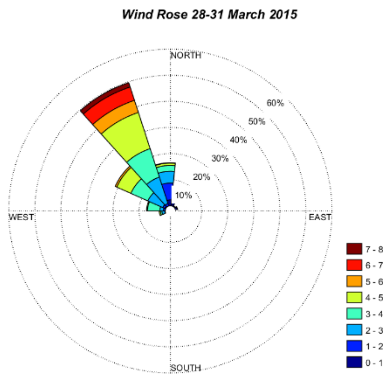


Figure 49 - Wind Roses in the days: a) 4th to 5th March;

b) 28th to 31st March.

There was no precipitation during these time intervals (Figures 50 and 51).

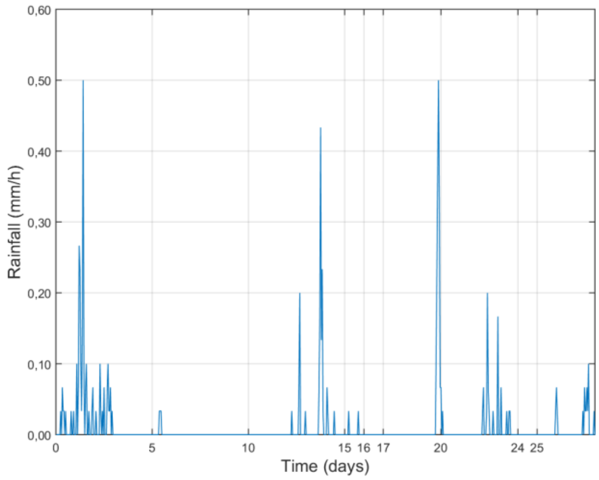


Figure 50 - Rainfall (mm/h), February 2015.

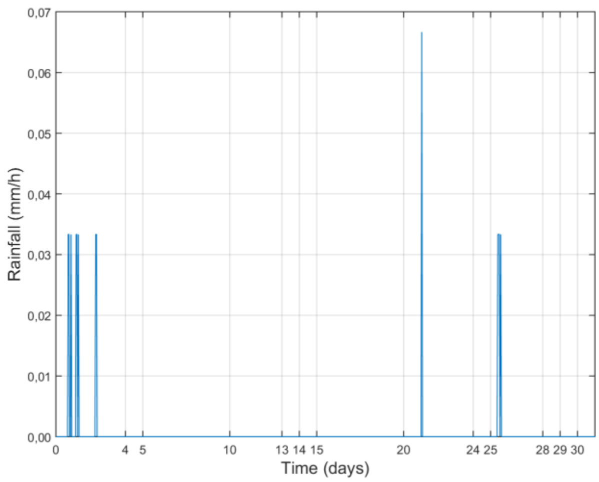


Figure 51 - Rainfall (mm/h), March 2015.

5.4.3 Maximum and Minimum Sea Surface Elevation and Residuals

The highest and lowest values of water level and residuals were determined for each year under study (Tables 5 and 6), comparing the dates in which these values occurred with the occurrence of spring tides.

Table 5 - Maximum and minimun annual SSE, from 2012 to 2017.

	SSE (m)	Barra	Ponte Varela	Chegado	Rio Novo	Vagueira	Vista Alegre
2012	Maximum annual SSE	3.97 12 Dec.	3.66 14 Dec.	3.77 14 Dec.	4.01 14 Dec.	3.95 17 Oct.	3.56 15 Dec.
	Minimum annual SSE	0.27 9 Mar.	1.05 11 Nov.	1.01 28 Nov.	0.704 31 Aug.	1.06 31 Aug.	1.20 3 Dec.
2013	Maximum annual SSE	3.86 29 Mar.	3.60 22 Oct.	3.88 21 Aug.	4.17 30 Mar.	3.90 19 Jan.	3.62 19 Jan.
	Minimum annual SSE	0.42 23 Jun.	0.64 18 Sep.	0.97 5 Sep.	0.53 23 Jun.	1.03 9 Feb.	0.59 19 Sep.
2014	Maximum annual SSE	4.01 4 Jan.	3.77 04 Jan.	3.88 12 Aug.	-	3.95 10 Sep.	**3.92** 3 Feb.
	Minimum annual SSE	0.36 26 Jul.	0.95 26 Mar.	0.69 13 Jul.	-	1.08 4 Oct.	1.09 27 Feb.
2015	Maximum annual SSE	4.01 26 Oct.	3.69 31 Oct.	3.78 15 Sep.	4.04 27 Oct.	4.03 27 Oct.	3.77 31 Aug.
	Minimum annual SSE	0.25 18 Fev.	0.74 15 May	0.47 19 May	0.74 31 Aug.	1.03 16 May	1.05 17 Feb.
2016	Maximum annual SSE	**4.09** 11 May	**3.86** 8 May	**3.97** 15 Dec.	**4.20** 8 May	4.07 11 Jan.	3.71 8 May
	Minimum annual SSE	0.24 13 Mar.	0.90 29 Sep.	0.46 16 Nov.	0.72 14 Nov.	1.06 8 Mar.	1.25 19 Jun.
2017	Maximum annual SSE	3.88 13 Fev.	3.67 12 Fev.	3.68 2 Jan.	3.88 12 Feb.	**4.38** 28 Mar.	3.53 13 Fev.
	Minimum annual SSE	0.24 22 Jan.	0.78 12 Mar.	0.46 15 Jan.	0.77 13 Mar.	1.06 13 Mar.	1.20 13 Mar.

It has been verified that the highest values found annually happen after the occurrence of a Full Moon or a New Moon, with intervals from one to three days, but the lowest values usually occur one or four days before a Full Moon or a New Moon. In 2016, the highest annual SSE occurred in relation to the years under study, except for Vista Alegre, where the highest value was found in 2014 and for Vagueira that was found in 2017.

Table 6 - Maximum and minimun annual residual values, from 2012 to 2017.

	SSE(m)	Barra	Ponte Varela	Chegado	Rio Novo	Vagueira	Vista Alegre
2012	Maximum annual	1.94 17 Aug.	0.67 14 Dez.	0.55 17 Oct.	1.43 21 Jun.	1.28 19 Apr.	0.53 14 Dez.
	Minimum annual	-1.88 4 Jun.	-0.57 16 Apr.	-0.66 2 Dez.	-0.82 24 Apr.	-1.62 17 Apr.	-1.49 3 Aug.
2013	Maximum annual	1.64 27 Mar.	1.22 19 Jan.	1.25 24 Dez.	2.22 30 Mar.	1.62 19 Jan.	1.34 19 Jan.
	Minimum annual	-1.35 14 Jan.	-1.46 18 Set.	-1.91 2 Aug.	-1.92 4 Dez.	-2.09 1 Mar.	-1.12 19 Jan.
2014	Maximum annual	2.12 22 Set.	1.57 5 Dez.	0.81 22 Mar.	-	1.65 15 Fev.	1.23 3 Jan.
	Minimum annual	-2.09 26 Jul.	-1.90 30 Jan.	-1.19 14 Aug.	-	-1.99 28 Fev.	-1.47 17 Aug.
2015	Maximum annual	2.70 20 Jan.	0.75 4 May	1.25 27 Oct.	0.690 4 May	1.84 23 Jan.	1.42 14 Dez.
	Minimum annual	-2.93 21 Jan.	-0.61 15 May	-1.49 15 May	-0.66 20 May	-2.26 25 Jan.	-1.58 9 Dez.
2016	Maximum annual	0.51 10 Jan.	0.93 10 Jan.	1.62 15 Dez.	2.34 11 Jan.	0.87 16 Jan.	0.52 8 May
	Minimum annual	-0.28 14 Mar.	-0.76 29 Jul.	-1.80 18 Nov.	-0.85 27 Set.	-0.81 29 Set.	-0.52 1 May
2017	Maximum annual	2.23 11 Jan.	0.57 13 Feb.	0.42 27 Jan.	0.62 12 Fev.	0.86 19 Mar.	0.53 13 Fev.
	Minimum annual	-2.69 6 Jan.	-0.44 12 Mar.	-0.46 16 Jan.	-0.41 14 Jan.	-0.33 1 Mar.	-0.32 16 Jan.

Looking at the residual values presented in Table 6, they generally occurred at the same time as SSE, that is, the highest values found occurred in days after a spring tide and the lowest in the days before.

Some exceptions were verified: on January 19th, 2013, in the stations of Ponte Varela, Vagueira and Vista Alegre, the values of the residuals coincide with the meteorological tide occurred on that date; In the same year, on Chegado, the highest value of the residual was on December 24th, the date when there was also a meteorological tide; These events were generated remotely, their effect being felt throughout the lagoon, which reflected on the results obtained.

6. Conclusions

To study the tidal changes induced by geomorphologic modifications between 1987/88 and 2017, the variations in the main constituents of tide in Ria de Aveiro, namely the semidiurnal tides (M_2 and S_2), the shallow water tides M_4 and M_6, and the fortnightly spring/neap tide cycle (MSf) was studied.

The semidiurnal tidal constituents, M_2 and S_2, are the most relevant for studies on tide changes, due to variations in the geomorphology of Ria de Aveiro, since they are the major constituents of the total tidal energy, as reported in the analysis of the Fourier spectra. By analysing the amplitude and the tidal phase variation of M_2 and S_2 between 1987/88 and 2002/03, it verified that there is an amplitude increase and a decrease of the phase, in all the stations studied.

Dredging in 1998, which increased the depth of the main navigation channels appears to be the most important factor contributing to these results, since the greatest variations occurred between 1987/88 and 2002/03. This means that as the main channels become deeper, the tidal wave amplitude increases, and its propagation becomes faster.

From 2002/03 to 2017, the amplitude and phase remained practically constant, showing that the extension of the north jetty by 200 m in 2012, did not induce significant changes in the dynamics of the tide along the lagoon.

Although the energy of the shallow water tidal constituents is low, these constituents must also be considered, since the bottom friction modifies the propagation of the tidal wave along the lagoon channels. In the studied tide gauges, the amplitude of constituents M_4 and M_6 increased between 1987/88 and 2002/03. This trend is justified by the transfer of part of the energy from M_2 to the constituents M_4 and M_6. Despite this trend, there was a decrease in the amplitude of these two constituents in Barra and Vagueira. This can be justified by a reduction of the bottom friction due to the increase of the channel depth from Barra to Vagueira and specifically in the area where the tide gauges are located, resulting of dredging operations throughout the lagoon in 1998.

The phase of the constituent M_4 decreased in all the stations between 1987/88 and 2002/03, except for Rio Novo. For the constituent M_6, from 1987/88 to 2002/03, the phase increased in the Cais do Bico/Chegado, Vagueira and Rio Novo and decreased in the other stations. Between the years of 2012 and 2017, the amplitude and phase values of the constituents, M_4 and M_6, remained practically constant.

The tidal constituent MSf, represents the variation of the water level in a spring / neap tide cycle, and is influenced by M_2 and S_2. A decrease in the amplitude from 1987/88 to 2002/03 can be observed in most the studied places, except for Ponte Varela. Between 2012 and 2017 the amplitude of this constituent increased in all the tide gauges, which means that in this time interval the difference in amplitude between the spring tides and the neap tides has been increasing.

The increase or decrease of the bottom friction will also change the tidal velocities along Ria de Aveiro channels, making the velocity of the flood and ebb tides unequal, giving rise to the asymmetry of the tide. This inequality will depend on phases of the M_2 and M_4 constituents. Tidal asymmetry often plays a key role in determining sediment transport and deposition/erosion patterns in several tidal dominated estuaries and inlets.

The results of this work show that in 1987/88 all stations located in the channels of the lagoon are flood-dominant, except for Barra that is ebb-dominant from 1987/88 to 2017.

From this date onward, it can see that while the Ponte Varela, Vagueira and Vista Alegre stations still remain flood-dominant, which means that the maximum velocity during the flood is higher than during the ebb and thus the sediment transport is done upstream, the Rio Novo and Chegado stations show ebb dominance, which translates in higher velocity during the ebb rather than the flood, and as such the sediment transport is preferentially done downstream which increases the erosion in those places. In Barra was ebb-dominating between 1987/88 and 2017.

Also, by analysing the values of Form number over these years, the results show that the tide is predominantly semidiurnal in all lagoon, between 1987/88 and 2017. There are two high tides and two low tides in a period of 12h and 25 minutes, which corresponds to a half of a lunar day.

The frequency of occurrence of storm surge phenomena between 2012 and 2017 was determined and the meteorological factors that influenced the generation of meteorological tides were studied, among them the variation in atmospheric pressure and wind intensity and direction.

Through the analysis of the tidal residuals it was verified that positive anomalies are more frequent than negative anomalies. From the different events occurring between 2012 and 2017, only two positive storm surges influenced the entire lagoon (January and December 2013), having been influenced by adverse meteorological conditions verified at national level. The remainder were manifested only locally in October 2012, March 2013, September 2015 and May 2016. The events with negative anomalies occurred in a smaller number.

The response of the residual water level to barometric pressure is found to be most significant during periods of low pressure systems. The effect of invert barometer is checked, that is, a decrease in atmospheric pressure induces an increase in water level and vice-versa. Also, it has been found that when the atmospheric pressure decreases or increases in small time intervals (approximately 24 hours), the effect is more visible, especially in positive storm surges. Wind is also a determining factor, and it has been verified that high intensity and long duration winds affect the lagoon. In relation to wind direction, the predominant ones were NW, SW, W and S, the wind tension can induce the accumulation of water at the banks of the channels.

The Ponte Varela area was the place where most locally generated events took place. This may be related to local conditions, such as: the width of the channel, which is the largest when compared to the rest of the lagoon, with an unobstructed distance over which the wind can blow in a certain direction, increasing the size of the water slope on one side of the channel. Additionally, the surrounding area is more unprotected, and the absence of high vegetation and /or housing or other infrastructure, makes Ponte Varela a place where wind propagation is most felt.

From the analysis of all the studied events, it was verified that the higher values of the sea water level and of residual values did not result from the existence of meteorological tides, but due to the spring tides. Exception for the event that occurred between January 18th and 19th, 2013 whose highest values of SSE and residual dues at Vagueira and Vista Alegre stations were recorded at that date.

Therefore, the interaction of a positive storm event at high tide with a spring tide will be risky event, which may influence the occurrence of marginal flooding in the lagoon.

The existence of tide gauges located along the main channels of the Ria de Aveiro, during the time intervals studied, would have helped to analyse the evolution of the tide from the inlet to the head of the different channels, and in the study of its variation with the geomorphological changes that the lagoon has been suffering over the last years and would have been a plus for this thesis.

The possibility of installing a large number of tide gauges along the channels of the Ria de Aveiro will enable a more comprehensive analysis of the various changes that this natural system will suffer, either by natural or anthropogenic modifications.

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8. Annexes

Some failures were observed in the operation of the tide gauges between 2012 and 2017. These failures include problems in the operation of the tide gauges, but are also related to changes in the infrastructure in the places where they were placed. The dates with the measurement failures are presented in Table 7.

Table 7 - Time intervals in which data collection failed

Stations (2012)	**Failures-start**	**End**
P. Varela (01/04 00:00)	01/06 16:00	02/06 16:00
Chegado (15/04 00:00)	08/05 15:00	09/05 08:00
Rio Novo (01/04 00:00)	3/05 13:00 8/06 14:00	6/05 15:00 21/06 00:00
Vagueira (01/04 00:00)	4/05 11:00 1/6 11:00	7/05 15:00 2/6 12:00
V. Alegre (01/04 00:00)	-	-

Stations (2013)	**Failures-start**	**End**
P. Varela	-	-
Chegado	-	-
Rio Novo	24/10 17:00 18/12 14:00	21/11 13:00 31/12 00:00
Vagueira	-	-
V. Alegre	-	-

Stations (2014)	**Failures-start**	**End**
P. Varela	04/11 13:20 14/11 01:20	05/11 14:40 25/11 17:00
Chegado	01/03 03:20 03/11 15:00	20/03 13:00 25/11 18:00
Rio Novo	01/01 00:00	31/12 00:00
Vagueira	06/01 11:00 25/01 23:20 01/03 00:00	07/01 11:40 03/02 16:20 06/03 07:40
V. Alegre	18/04 02:20 20/08 12:40	23/04 12:40 01/12 00:00

Stations (2015)	**Failures-start**	**End**
P. Varela	-	-
Chegado	20/02 19:40 27/04 15:20 25/10 16:40	13/03 09:40 29/04 13:20 27/10 15:00
Rio Novo	01/01 00:00	29/04 09:00
Vagueira	17/02 00:00	13/03 12:40
V. Alegre	01/09 00:00	31/12 23:40

Stations (2016)	**Failures-start**	**End**
P. Varela	**-**	**-**
Chegado	19/02 12:40 07/09 07:00	22/02 10:40 07/09 10:00
Rio Novo	19/02 10:40 14/11 14:40	23/02 14:20 14/11 15:20
Vagueira	22/07 11:20	29/07 16:40
V. Alegre	04/04 13:00	07/04 13:20

Stations (2017)	**Failures-start**	**End**
P. Varela	-	-
Chegado	08/02 10:20	01/03 12:40
Rio Novo	-	-
Vagueira	-	-
V. Alegre	-	-