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Article

Characterizing Seiches Oscillations in a Macro-Tidal Estuary

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Abstract: Seiches oscillations may account for an important proportion of sea level variations in nearshore environments, inducing overflow and surges while impacting the safety of marine areas. However, complementary investigations are still required to characterize seiches in coastal basins, including especially estuaries. The present study exhibited seiches characteristics in the intertidal zone of the upper Elorn estuary (western Brittany, France), within the city of Landerneau, which is regularly subjected to river overflow and inundation. This investigation relied on five-year measurements of the free-surface elevation. As recorded time series were highly discontinuous around low tide, an original data analysis technique was implemented to exhibit seiches characteristics during the different tidal cycles. Measurements revealed important seiches oscillations with heights liable to exceed 0.6 m and periods of around 45–70 min. Seiches showed furthermore a fortnightly variability with pronounced heights and an increased number of oscillations during neap tides. These variations appeared, however, to be disturbed by the additional effects of meteorological conditions, including especially the influence of wind. The number of oscillations around high tide was thus found to increase in strong wind conditions. These effects were particularly noticeable at low atmospheric pressure, suggesting a sensitivity of seiches to wind meteorological patterns during cyclonic events.

Keywords: seiches; tide; wind; estuary; wetting-drying areas; western Brittany; Elorn; Landerneau; bay of Brest

Citation: Guillou, N.; Chapalain, G. Characterizing Seiches Oscillations in a Macro-Tidal Estuary. *Coasts* **2024**, *4*, 108–126. https://doi.org/10.3390/coasts4010007

Academic Editor: Kamal Djidjeli

Received: 20 December 2023
Revised: 24 January 2024
Accepted: 4 February 2024
Published: 7 February 2024

1. Introduction

Among the different physical mechanisms impacting sea-level variations in nearshore waters (including tides, waves, and surges), seiching appears as a particular hydrodynamic process. Indeed, it is characterized by oscillations with heights and periods highly dependent on the configuration of coastal basins (in length, depth, and contour) [1]. Seiches are typically defined by periods lasting from a few minutes to more than one hour (between the longest storm waves and tides). Furthermore, it shows reduced heights, most of the time restricted to a few centimeters. Thus, associated water level fluctuations usually go unnoticed. However, these oscillations may sometimes exceed 0.2 m or more, competing with tide-induced variations. In these conditions, the total sea level reached during high tide may vary very quickly (matching seiches temporal variations) while increasing current speeds and exceeding the height of natural coastal defenses and structures. Seiches may therefore contribute to coastal flooding in low-lying areas and/or impact the safety of sensitive locations, such as harbors. Thus, it may induce damages to infrastructure or fixed and floating installations (in particular ships and vessels subjected to pulling forces on mooring ropes) [2,3]. Further effects are also expected on water circulation patterns, associated mixing, energy recovery, and the redistribution of salinity, dissolved oxygen, sediments, and nutrients [4–8].

Seiches typically occur as the resonance of a water body disturbed by a series of external meteo-oceanographic forcings, including, among others, (i) local/remote variations in meteorological conditions [4,9], or (ii) internal wave activity in stratified waters [10]. Seiches may thus appear in conditions with rapid changes in wind intensity and/or atmospheric pressure. In these conditions, coastal basins may be subjected to oscillations of the water surface, with periods liable to be reduced to a few minutes and seconds [1]. But seiches may also be generated from deep-sea internal waves and associated induced currents at the shelf break [11]. For tidally generated solitary waves, the height of coastal seiches may be correlated with the spring-neap tidal cycle. Seiches oscillations may furthermore show seasonal variations in relation to stratification effects liable to impact (i) the generation of deep-sea internal waves and (ii) open-boundary conditions of coastal basins [12].

Seiches properties in heights and periods were therefore characterized by high temporal variability, resulting from the modes and processes of influence of external exciting sources on coastal basin configurations. Investigations on seiches were adapted to the physical properties of the marine environment. Studies on seiches were thus dedicated to a variety of coastal basins, including harbors, lakes, bays, tropical lagoons, semi-enclosed or internal seas, and estuaries. Given the relative inaccuracy of process-based physical models in the approach of seiches, these investigations primarily relied on high-frequency observations of sea-surface elevations. Thus, by exploiting tidal gauge measurements, studies conducted within harbors exhibited seiches oscillations with periods below 10 min. These investigations also provided further insights into the relationship between harbor seiches and atmospheric pressure variations or wind/waves exposure, including especially infragravity waves [13–17]. Complementary investigations were conducted in bays and estuaries by focusing on the characteristics, properties and mechanisms of seiches generation and occurrence [2,4,18–22]. As for harbors, seiches oscillations in these environments may be strongly influenced by meteorological patterns and disturbances. This includes, especially, the rapid variations in amplitude and direction of the wind velocity. These effects were particularly noticeable for wind variations at the time scale of minutes, which were found to impact the strength of seiches oscillations. In estuaries, additional exciting sources may also arise from the complex interactions between tidal inflow, low-frequency fluctuations, and the internal structures of the estuarine channel (such as meanders, vegetation, and banks). However, further investigations are still required to characterize seiches in estuarine environments.

The present investigation complements these different studies by focusing on seiches oscillations in the upper part of a small macro-tidal estuary located in western Brittany (France, Figures 1 and 2). The site of application is the intertidal zone of the upper Elorn estuary, within the city of Landerneau. This location is regularly subjected to inundation events during combined spring tides and strong river discharges. The approach of river overflow and inundation in this area is of high concern as these events impact the safety of inhabitants, economic activity, urban transport, and surrounding goods and materials. Besides being subjected to the influences of macro-tidal regimes and river discharges, the Elorn estuary is also characterized by a complex topography and bathymetry, with extended wetting-drying areas, liable to increase the generation of seiches (Figure 2). Observations of the free-surface elevation within Landerneau thus revealed important seiches oscillations with heights liable to exceed 0.4 m and periods of around 45–70 min (Figure 3). These oscillations were particularly noticeable during neap tidal conditions. In order to describe the mechanisms involved in seiches oscillations, we exploited a series of high-frequency observations of the free-surface elevation. These measurements were collected during a period of five years (between 2017 and 2022). As measurement points were located in wetting-drying areas, recorded time series were highly discontinuous around low tide. An original analysis technique was thus implemented to characterize seiches (in heights and number of oscillations) during the different high tides. Particular attention was dedicated to the evolution of high-frequency oscillations with respect to tidal regimes and meteo-oceanographic conditions. These evolutions were assessed at the semi-diurnal, fortnightly, and seasonal time scales. Beyond the local interests in mitigating inundation risks, such an investigation may provide further insights into the approach of seiches oscillations in estuarine environments. It may also help to characterize the physical mechanisms at the origin of the generation of seiches in these environments.

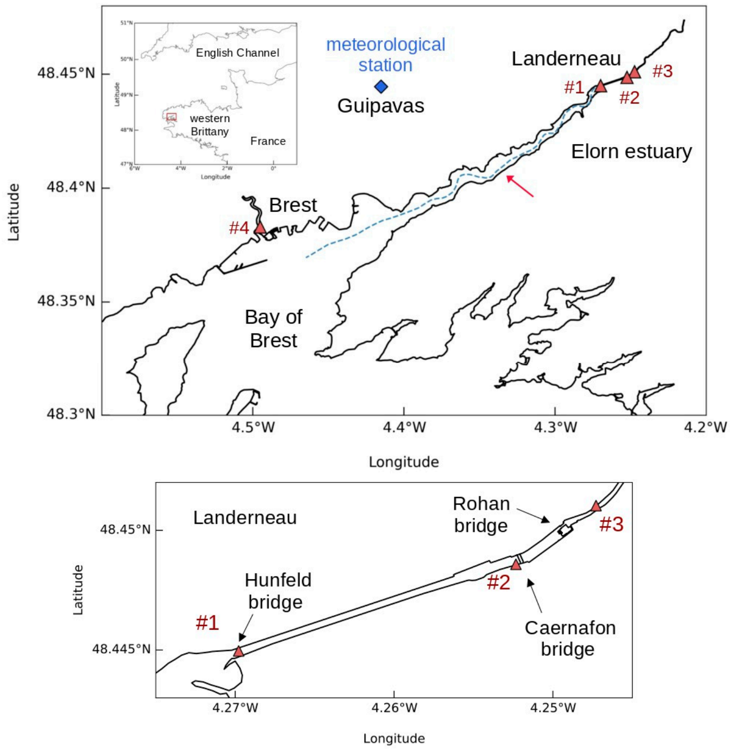

Figure 1. Area of interest covering (**top**) the bay of Brest and the Elorn estuary with (**bottom**) a detailed view of the upper estuary and the city of Landerneau. Locations of measurement points #1–#4 of free-surface elevation are shown with red triangles. The location of the meteorological station of Guipavas appears as a blue square. The blue dotted line along the estuary shows the locations of points retained for the extraction of bed elevation in Figure 4. Please note that this line ends at point #1. The red arrow finally indicates the location of the stair margin within the access channel to the estuary.

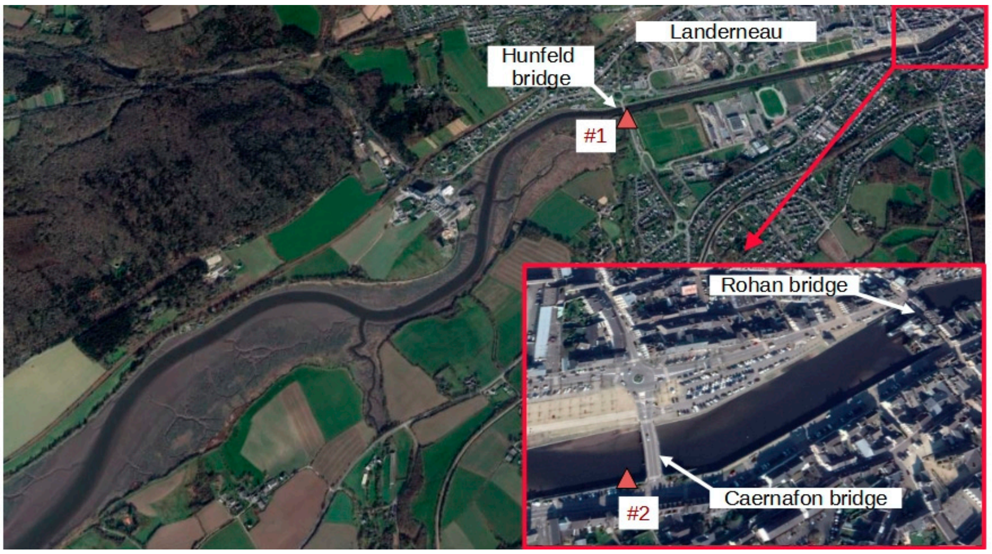

Figure 2. Google Earth maps showing the upper Elorn estuary with a detailed view of the center of the city of Landerneau downstream the Rohan Bridge. Locations of measurement points are shown with red triangles according to Figure 1. The bottom-left side of this figure exhibited furthermore a part of wetting-drying areas bordering the access channel to the estuary around low tide.

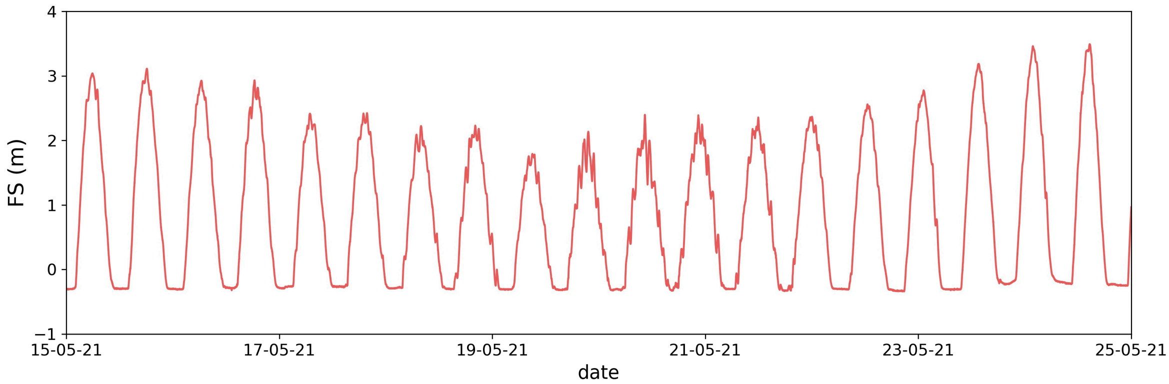

Figure 3. Detailed view of time series of observed free-surface (FS) elevation between 15 May 2021 and 25 May 2021 at point #2 in Landerneau downstream the "Pont de Rohan". Measurements are shown with respect to the French IGN reference ("Institut Géographique National").

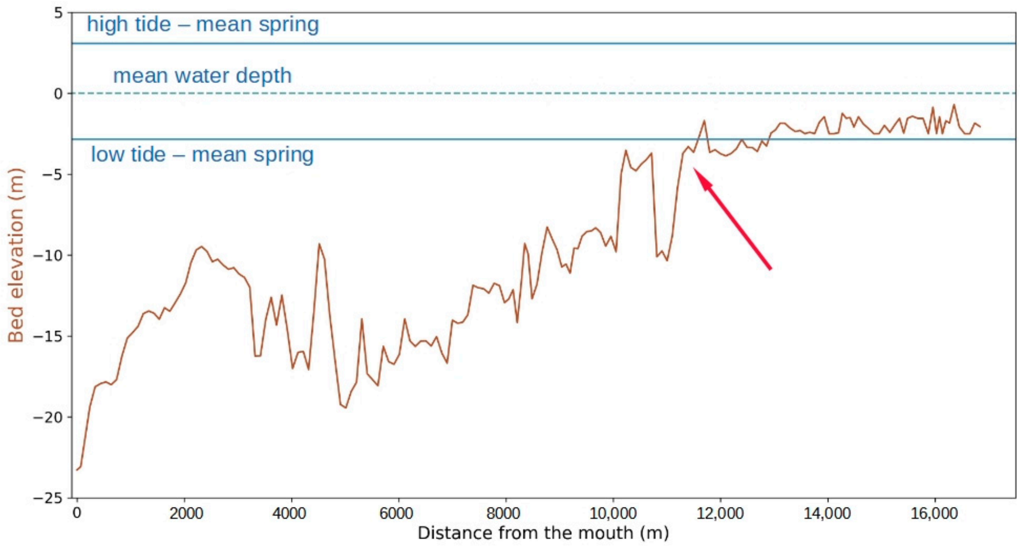

Figure 4. Evolution of the bed elevation (referenced with respect to the mean water depth) in the access channel to the Elorn estuary from its mouth to its upper part (point #1). Points retained for this extraction are located along the blue dotted line shown in Figure 1. The red arrow shows the position of the local threshold identified in the upper estuary. The high and low water levels are furthermore indicated for mean spring tidal conditions.

The paper is organized as follows. Section 2 describes the study site, focusing on environmental conditions including bathymetry, tidal forcings, and meteo-oceanographic patterns. Section 3.1 presents the available observations of free-surface elevation exploited to characterize seiches oscillations. Section 3.2 describes the analysis techniques retained to extract seiches characteristics around high tide. This includes (i) an original method dedicated to exhibiting the height and the number of seiches oscillations during the different tidal cycles and (ii) a spectral analysis implemented to approach the first and second mode periods of seiches. Section 4 shows and discusses the results obtained. Particular attention was first dedicated to the evolution of seiches from the mouth to the upper part of the Elorn estuary. The occurrence of seiches (in height and number) was then analyzed with respect to the tidal cycles. We finally investigated the potential correlations with local and/or remote forcings, including meteorological conditions.

2. Study Area

The site of application is located in the upper part of the Elorn estuary within the city of Landerneau (Figures 1 and 2). The portion of the estuary here studied extends over a total length of 17 km, with a width varying from around 1.8 km at its mouth near the harbor of Brest to less than 50 m within Landerneau. In Landerneau, the width of the river is constrained by the quays of the city, which were initially set up to support an ancient harbor activity. The Elorn estuary is furthermore characterized by large wetting-drying areas bordering an access channel with local seabed features and stair margins (Figures 1, 2 and 4). Thus, in the access channel, after a local rise of the bathymetry at the entrance of the estuary, the bed elevation follows a linear trend varying from around 20 m to less than 8 m (with respect to the mean water depth) along a distance of around 6 km. This linear evolution stops around 11 km from the mouth of the estuary. In this location, the bathymetry is characterized by a local threshold with a height liable to reach 5 m. The bed elevation presents reduced variations after this margin. In the city of Landerneau, the channel characteristics are finally constrained by the presence of a notable civil engineering structure, the inhabited Rohan Bridge, which restricts the tidal propagation. Thus, in this location, the bathymetry shows a local threshold sloping with a height above 3 m, and the river section is reduced by more than 50%.

The hydrodynamic conditions of the estuary are dominated by the effects of the tide. The Elorn estuary is thus a macro-tidal environment characterized by a spring tidal range exceeding 6.5 m at its mouth and spring tidal currents over 1 m s^{-1} in its center part [23]. Along the access channel to the estuary, the evolution of the free-surface elevation exhibited a flood/ebb asymmetry. This asymmetry resulted from a time delay at low tide, partly associated with a reduced celerity of surface waves in shallow waters. At the mouth of the estuary, tidal currents show a symmetric distribution between peak ebb and flood. However, increased variability was exhibited in the upper estuary from the interaction between tidal propagation and river flows. This variability is mainly associated with the evolution of river discharges. Thus, in spite of a reduced mean annual rate estimated at around 6 m^3 s^{-1}, the river discharges may vary significantly, with (i) daily-averaged values liable to exceed 70 m^3 s^{-1} and (ii) monthly-averaged values over 10 m^3 s^{-1} during the winter period [24–26]. Further effects, such as stratification events, may also influence the hydrodynamic conditions of the estuary. These events are highly dependent on tidal strength. Indeed, major stratification events appear when tidal conditions (i) do not allow sufficient intrusion of marine waters within the estuary and (ii) restrict the mixing between sea and estuarine waters. This occurs typically during neap tides combined with high river discharges and/or thermal gradients [27]. The estuary is characterized by a reduced exposure to wind-generated surface-gravity waves propagating offshore western Brittany within the bay of Brest [28]. However, estuarine hydrodynamic conditions may be influenced by meteorological patterns, including variations in atmospheric pressure and wind velocity. Thus, the harbor of Brest, located at the mouth of the Elorn estuary, may be subjected to pronounced surges liable to exceed 1 m during storm events [29]. As higher wind velocity is distributed along a north-eastern/south-western direction—matching the orientation of the estuary (Figure 5), variations in wind amplitude are also likely to influence estuarine hydrodynamic conditions.

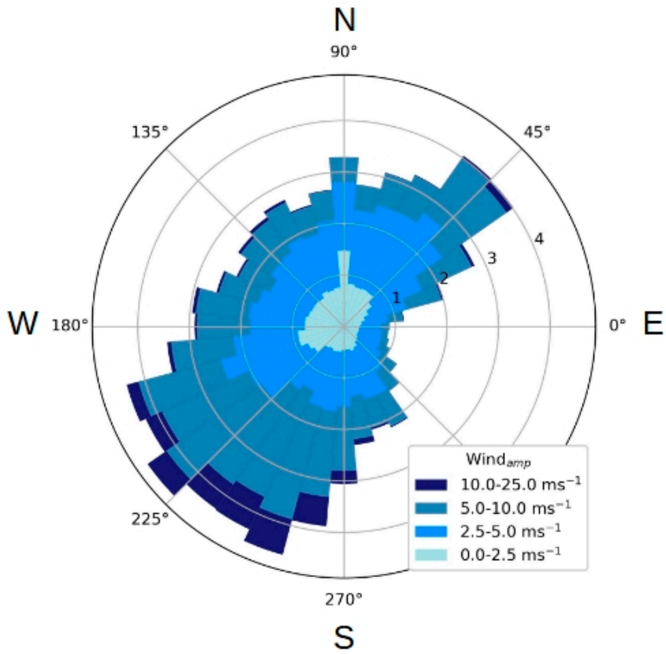

Figure 5. Distribution in amplitude and direction (incoming wind direction) of the 10 min averaged wind velocity observed at the meteorological station of Guipavas over the period 2017–2022.

3. Materials and Methods

3.1. Measurements

3.1.1. Free-Surface Elevation

The investigation relied on observations of the free-surface elevations gathered as part of a global monitoring system set up by the Laboratory of Coastal Engineering and Environment (Cerema, "Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement") in the bay of Brest and the Elorn estuary. Observations here exploited were collected with Vega radar level sensors (Vegaplus WL 61) implemented in three locations within the city of Landerneau: (i) At the downstream entrance of the urbanized area near the Hunfeld Bridge (point #1), along the quayside downstream (point #2), and upstream (point #3) at the Rohan Bridge (Figures 1 and 2). Observed surface elevations are nearly similar at points #1 and #2 (Figure 6). However, increased differences are obtained at point #3, located after the local threshold of the Rohan Bridge. Indeed, in this point location, the influence of the tide is restricted to the highest water depth, typically during spring conditions. At the three measurement locations, data were acquired with a time step varying between 10 and 60 s. As exhibited in Figure 6, measurements collected between 2017 and 2022 cover different blank periods associated with system implementation and malfunction or maintenance operations. However, besides the high-temporal resolution of the data acquired, these observations integrate a significant number of spring-neap tidal cycles for varying meteo-oceanographic conditions. It thus represents a valuable source of information to characterize seiches oscillations in the upper Elorn estuary. In the present investigation, particular attention was devoted to measurements acquired at point #2, located downstream the Rohan Bridge and characterized by the longest periods of available data. This location was further considered in a previous investigation [30] to assess inundation events within the city of Landerneau.

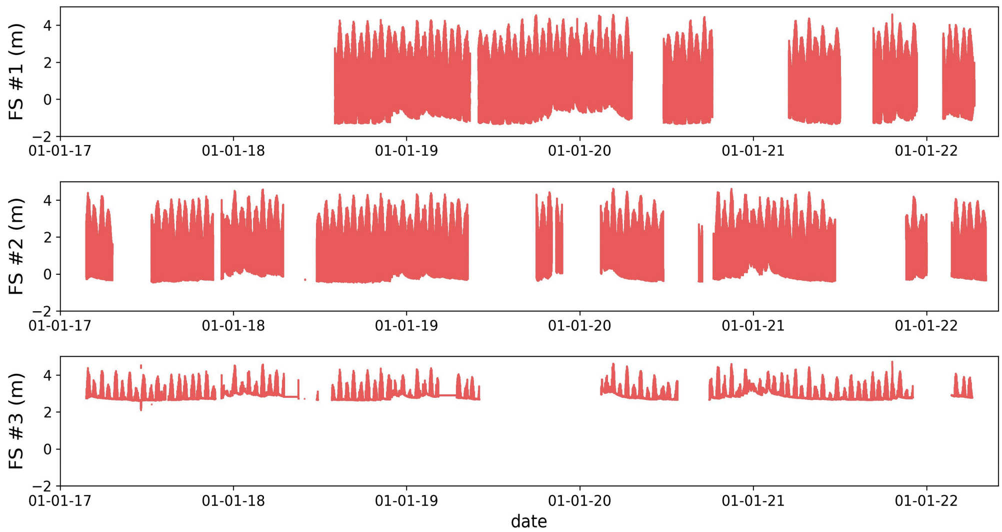

Figure 6. Time series of observed free-surface (FS) elevation between 2017 and 2022 at points #1, #2, and #3. Measurements are shown with respect to the French IGN reference.

Complementary observations were considered to characterize the evolution of free-surface variations along the Elorn estuary. Thus, to assess input conditions at the mouth of the estuary, we exploited measurements acquired at the tidal-gauge station of Brest harbor by the French navy SHOM ("Service Hydrographique et Océanographique de la Marine") [31]. These observations were conducted within a well attached to the harbor quayside to filter the effects of local waves and wind on the evolution of the sea surface. Besides constituting a reference database for the characterization of tides along the coast of France, these measurements can also be exploited to investigate the evolution of storm surges and seiches oscillations within Brest harbor [13]. Measurements of the free-surface elevation in this location were provided at a time interval of one minute.

The investigation finally considered the French tidal coefficient to assess tidal range variations. This parameter is calculated by the French navy SHOM from the ratio between (i) the half tidal range and (ii) the averaged value for equinoxic spring tides [32]. This latter value is equal to 6.1 m in Brest harbor, where this coefficient is computed. Thus, the tidal coefficient is a global indicator of tidal range variations along the coast of France. Its value increases with the tidal range. It varies between 20 and 120, with values of 95 for the mean spring tide, 45 for the mean neap tide, and 70 for the mean tide. Being computed in Brest harbor, this parameter is finally representative of tidal range variations in the area of interest.

3.1.2. Meteorological Conditions

In order to investigate the potential correlations between seiches oscillations and meteorological conditions, we exploited a series of high-frequency observations provided by Météo-France as part of a collaboration program with Cerema. Data consist of (i) 10 min averaged amplitude and direction of the wind velocity at 10 m above the bed and (ii) atmospheric pressure at the sea level. These observations were collected at the meteorological station of Guipavas (Figure 1) and provided with a time step of 6 min consistent with the main periods of seiches estimated at around 45–70 min from the visual analysis of the observed time series (Figure 3).

3.2. Data Analysis Techniques

As points considered in the upper Elorn estuary were located in wetting-drying areas, measurement time series were highly discontinuous around low tide. Thus, different methods and analysis techniques were applied to successively characterize (i) the evolution of seiches oscillations (in number and height) with respect to the tidal cycle and (ii) the main periods of observed high-frequency oscillations. These analysis techniques were applied to observational data interpolated with a regular time step of 60 s, consistent with the acquisition time step over the period 2017–2022 (see Section 3.1.1).

3.2.1. Analysis of Seiches with Respect to Tidal Cycles

As the upper part of the Elorn estuary within the city of Landerneau corresponds to wetting-drying areas, measurements conducted in these locations cannot be exploited during low tide (Figure 3). Thus, the analysis of seiches oscillations was performed by considering the different series of observations around high tide.

These different time series were first identified by retaining a minimum water level of 0.5 m with respect to the French IGN reference ("Institut Géographique National"). Such a reference level allows for the capture of the successive rise and fall of the water level around high tide during both spring and neap conditions. Matching Wijeratne et al. [33], these different time series were then subjected to a Butterworth filter with 3 min and 120 min cut-off periods to isolate seiches oscillations. Thus, the smoothed signal (without these short-period oscillations) was obtained by subtracting the initial observations from the output of the Butterworth filter (Figure 7). As variations with periods over 120 min were neglected, the resulting time series did not integrate the contribution of tidal harmonic components. The analysis was thus restricted to variations associated with seiches oscillations. The different signals were finally processed over a period of three hours, centered around peak maxima of smoothed variations. Processing consisted of extracting the number of oscillations with their heights for these different time series around high tide.

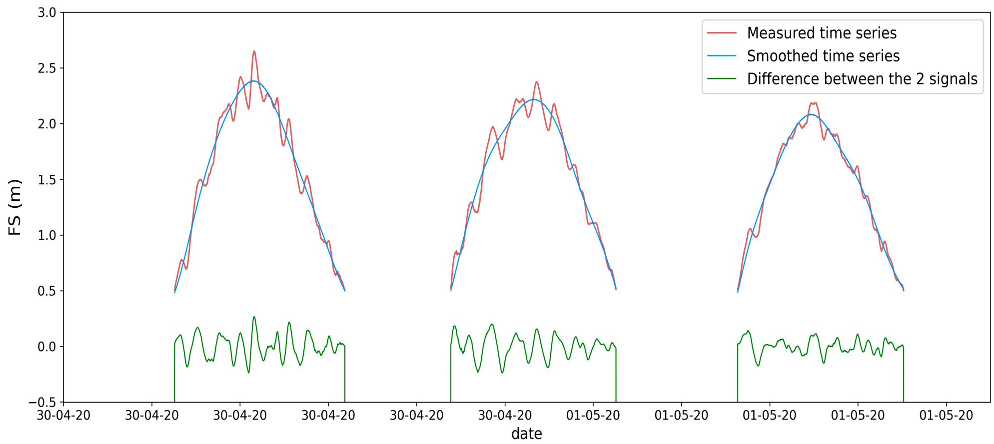

Figure 7. Detailed view of observed and smoothed (without seiches oscillations) time series of free-surface (FS) elevations at point #2 with the difference between the two signals exhibiting seiches oscillations with periods between 3 min and 120 min. This detailed view was shown between 30 April 2020 and 1 May 2020.

A seiche oscillation was identified as a maximum value between two minima. In the present investigation, the height of these variations was thus defined as the averaged difference between (i) a minimum and the next maximum and (ii) a maximum and the next minimum. Seiches were further identified for a height over a given limit, taken here as equal to the value of 0.05 m. Seiches were therefore identified as pronounced variations in the sea surface elevation around high tide. For the different time series, centered around high tide, we finally obtained (i) the number of seiches variations and (ii) the heights of these variations (including the averaged values) per tidal cycle.

3.2.2. Spectral Analysis Technique

The previous analysis is particularly useful to characterize the observed variations in the free-surface elevation associated with the effects of seiches. Thus, by exhibiting the characteristics of seiches per tidal cycle, it provides further information about the temporal variability of these oscillations. Such an analysis allows, therefore, a refined assessment of seiches temporal variations by identifying potential correlations with tidal regimes and other external exciting sources, including meteorological conditions. However, this analysis technique is restricted to bulk parameters, setting aside a detailed investigation of the spectral characteristics of seiches oscillations, especially the different mode periods. To complement the previous analysis technique, we conducted a spectral analysis of the series of signals extracted around high tide. This analysis derives the distribution of the power spectral density versus frequency and allows for the identification of the periods of major spectral peaks (Figure 8). This information is particularly useful to characterize the different resonance modes observed in the upper Elorn estuary.

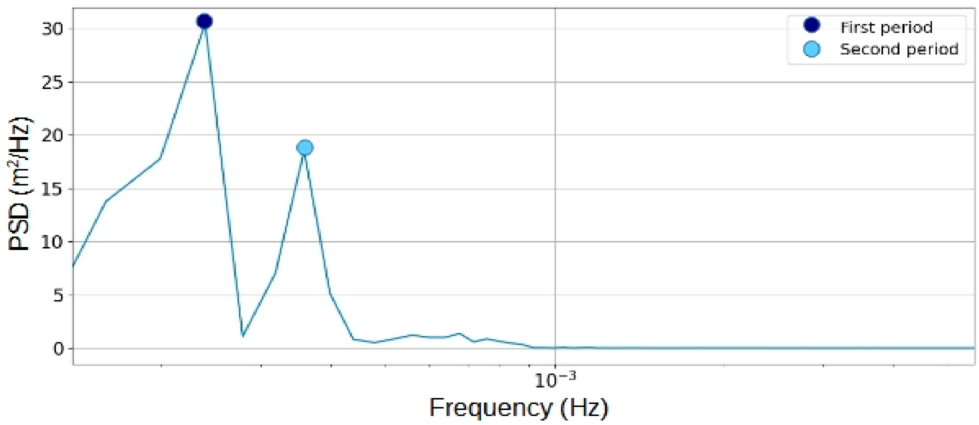

Figure 8. Illustration of the distribution of the power spectral density against frequency for a time series of seiches oscillations extracted around high tide (see Section 3.2.1). Locations of major spectral peaks retained for the extraction of the first and second mode periods are shown with blue circles.

4. Results and Discussion

4.1. Seiches Oscillations along the Elorn Estuary

As shown in Figure 9a, reduced differences were exhibited between the temporal variations in the free-surface elevations observed around high tide at points #1, #2, and #3. Thus, although being restricted to spring conditions, seiches oscillations at point #3 (upstream the Rohan Bridge) showed nearly the same temporal evolution around high tide as observed downstream at point #2. We also noticed reduced differences between points #2 (near the Rohan Bridge) and #1 (at the entrance of the urbanized channel section). Observed seiches oscillations appear therefore to propagate with reduced modifications between the quay sides of the channel within the city of Landerneau. More important differences appear, however, between the upper part and the mouth of the Elorn estuary. Thus, beyond the deformation and amplification of tidal harmonic components along the estuary, varying seiches oscillations were obtained between point #2 located downstream the Rohan Bridge and point #4 within the harbor of Brest (Figure 9b). Indeed, as exhibited by Devaux [34], seiches oscillations in Brest harbor were characterized by reduced heights (below 0.15 m) and periods (below 25 min). Thus, the associated temporal variations were hardly visible in the observed time series in Brest harbor. These oscillations contrasted with the observed temporal evolution of the free-surface elevation in the upper Elorn estuary, characterized by heights exceeding 0.40 m and apparent periods of around 45–70 min.

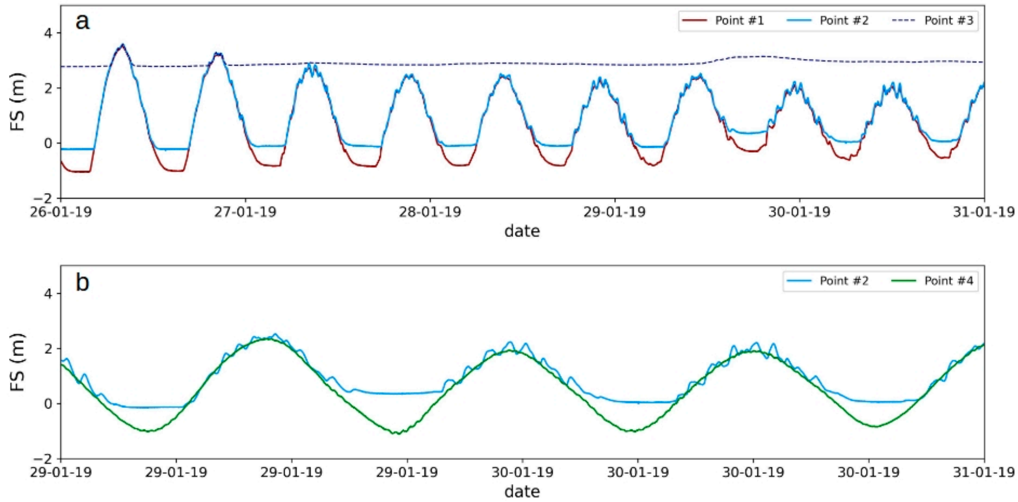

Figure 9. (**a**) Time series of observed free-surface (FS) elevations at points #1–#3 located in the upper Elorn estuary from 26 January 2019 to 31 January 2019. (**b**) Detailed view of time series of free-surface elevations at points #2 (upper estuary) and #4 (harbor of Brest) from 29 January 2019 to 31 January 2019.

These comparisons suggest that seiches are generated and propagate at the scale of a portion of the Elorn estuary. A local feature in the bathymetry may be at the origin of a part of these oscillations. Thus, as exhibited in Section 2 (Figure 4), the bathymetry along the estuary shows a bottom slope break at around 5.5 km from the entrance of the city of Landerneau (point #1). In order to provide further insights about seiches oscillations in the estuary, we applied Merian's formula for semi-enclosed basins: $T = 4L/\sqrt{gh}$ with g the gravity acceleration taken equal to $g = 9.81$ ms^{-2}, L the length of the water body taken here equal to 5.5 km, h the mean water depth considered at around 3 m in the upper estuary, and T the first mode period of seiches oscillations. With these features, we obtained an estimation of 67 min for this period, matching the range of oscillation periods observed during the successive high tides in neap tidal conditions at point #2 (Figures 3 and 9). This result was consistent with the estimation conducted by Le Hir et al. [23] and confirmed different investigations in broader bays and estuaries, including Alfacs Bay (NW Mediterranean Sea, Spain) [18]. Thus, it seems that the upper Elorn estuary behaves as a "quarter-wave" resonator with an antinode (speed node) within the city of Landerneau and a level node (speed antinode) downstream. As exhibited by Bowers et al. [35], tide may produce an oscillation at the natural period of the water body resulting in short-period variations around the time of the high water. These short-period variations contribute, in some cases, to the formation of double-high waters in shallow coastal locations. However, measurements in the upper Elorn estuary exhibited a wider range of apparent periods. It was therefore suggested that other mechanisms may be responsible for these high-frequency oscillations. Whereas further observations conducted along the estuary may be required to characterize the evolution of seiches, this analysis provides further insights about the potential generation of seiches in this environment. Given the negligible differences in observations collected within Landerneau, a detailed investigation of seiches characteristics and associated temporal variations was conducted by exploiting measurements at point #2.

As exhibited in previous sections, several different period peaks may be distinguishable in the oscillations spectrum of the free-surface elevation, including in particular (i) tide-induced variations with periods over 2 h and (ii) seiches oscillations with reduced periods. The spectral analysis technique described in Section 3.2.2 was applied to the measurement time series captured around high tide at point #2. The distribution of the power spectral density was analyzed to extract the first and second mode periods of seiches oscillations. For the first mode period, we obtained values mainly distributed between

45 and 70 min, consistent with the preliminary estimations derived from the observed time series (Figure 10). For the second mode periods, values were mainly restricted between 35 and 60 min. The first and second mode periods of seiches may thus appear over a wide range of values. This confirms a series of investigations conducted on seiches oscillations in estuaries [3,18,36]. The wide range of seiches mode periods suggested also an increased variability of the high-frequency oscillations with respect to external exciting sources, including in particular the tidal range and meteorological conditions. Thus, as exhibited by the application of Merian's formula, the mode periods of seiches may be influenced by tide-induced variations in the water depth. However, we also expected additional effects from the variations in atmospheric pressure and wind velocity. These different aspects were investigated in Sections 4.2 and 4.3.

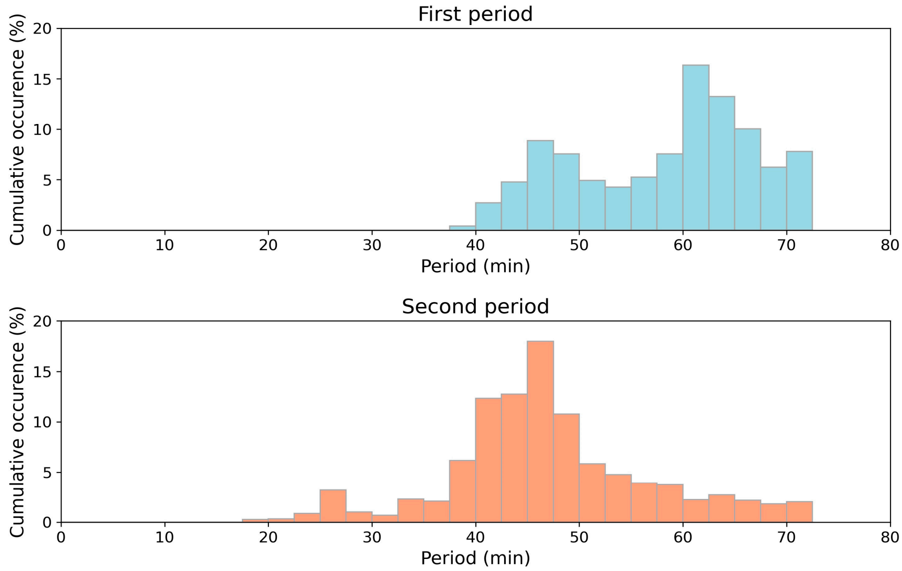

Figure 10. Distribution of the first and second mode periods (expressed in minutes) of seiches oscillations for the different time series extracted around high tide between 2017 and 2022.

4.2. Seiches Evolution with respect to Tidal Conditions

The first analysis technique described in Section 3.2.1 was applied to observations collected between 25 February 2017 and 5 May 2022 at point #2. Seiches characteristics obtained (height and number of oscillations per tidal cycle) were correlated with the evolution of the French tidal coefficient as an indicator of tidal range variations. Figure 11 shows the temporal evolution of the heights of seiches and the tidal coefficient over the period from July 2018 to April 2019. The heights of seiches appeared to be impacted by a fortnightly periodicity with a tendency for increased values during neap tides. This periodicity was particularly noticeable in early 2019, characterized by pronounced heights of seiches oscillations liable to exceed 0.70 m. This tendency was confirmed by the correlation between the heights or the number of seiches per tidal cycle and the tidal coefficient over the whole measurement period (Figure 12). Thus, neap conditions, with tidal coefficients below 70, were characterized by an increased number of seiches and associated heights liable to exceed 0.8 m over the whole measurement period. The proportion of noticeable seiches oscillations felt drastically for spring conditions with tidal coefficients over 100, with only two events exceeding 0.6 m. The number of seiches per spring tidal cycle was further restricted to 9 against more than 11 in neap conditions. The results obtained exhibited, therefore, a tendency for increased seiches oscillations (in height and number) during neap tidal conditions. These effects were naturally very visible during these periods of the tidal cycle characterized by a reduced tidal range.

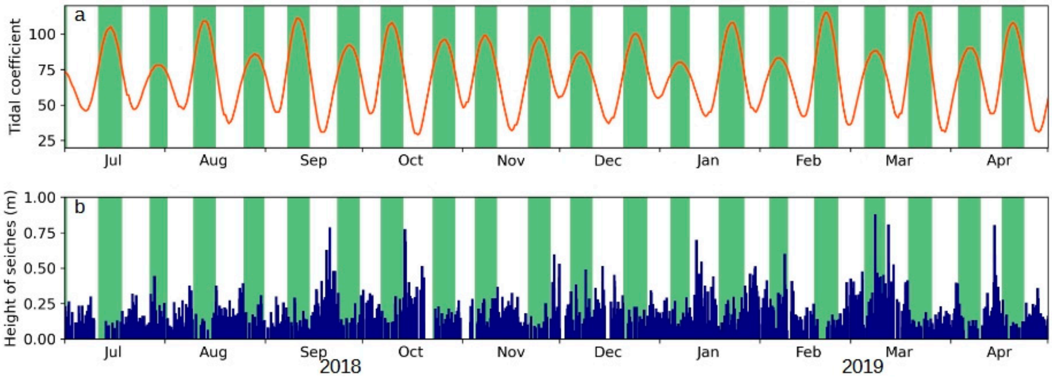

Figure 11. Time series of (**a**) tidal coefficient and (**b**) height of seiches over the period from July 2018 to May 2019. Periods of neap and spring tides were exhibited in the background figures by white and green bars, respectively.

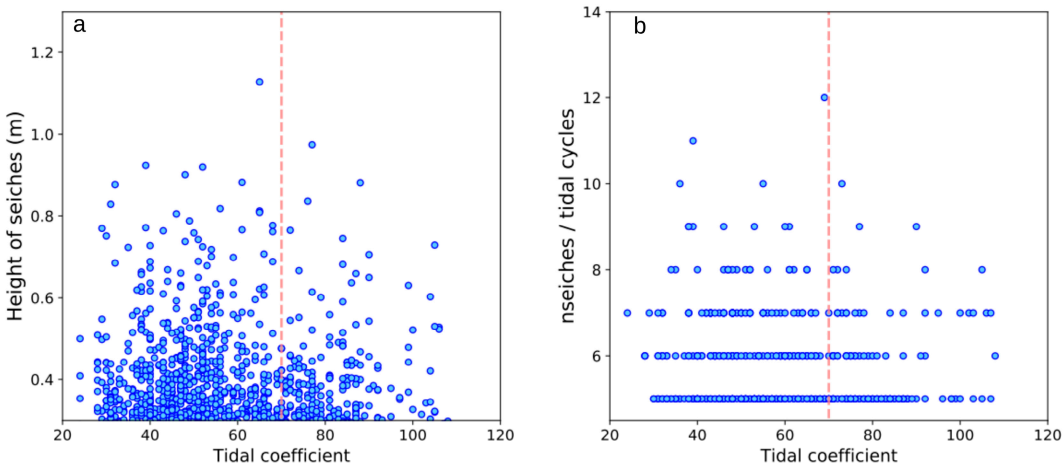

Figure 12. Correlation between (**a**) the height of seiches and the tidal coefficient and (**b**) the number of seiches per tidal cycle and the tidal coefficient. The vertical dotted line shows the limit with a tidal coefficient of 70.

The predominance of seiches oscillations during neap tidal conditions was revealed in a series of investigations, mainly dedicated to coastal island locations. Thus, by exploiting long-term tidal gauge observations around Magueyes Island (Puerto Rico), Giese et al. [10] exhibited one of the first proofs of fortnightly variations in seiches. Chapman and Giese [11] suggested that fortnightly variations with larger seiches during neap tides could be associated with tide-generated internal waves from distant sources. Following their theory, it was suggested that deep-sea internal solitary waves impinged on the submarine slopes near the shelf break and generated a horizontal current impulse that excited standing oscillations with increased amplitudes in the coastal area. This theoretical model was ascertained by recent investigations conducted by Wijeratne et al. [33] on the north-eastern coast of Sri Lanka or Alfonso-Sosa [37] in the Maldives Islands. However, in the present analysis, the relationship between seiches in the upper Elorn estuary and internal wave mechanisms at the shelf break cannot be ascertained. Indeed, the offshore region of western Brittany experiences strong internal tides liable to degenerate into solitons with frequencies ranging from a few minutes to one hour on the continental shelf [38,39]. Nevertheless, reduced evidence of associated signatures was found in the coastal areas of western Brittany, including especially the bay of Brest. Thus, in this region, Pairaud et al. [40] exhibited a reduced propagation of internal tides over the continental shelf and suggested that barotropic currents and stratification may play a role in these mechanisms. Nevertheless, as investigations on internal tides primarily focused on large-scale areas including the continental slope, shelf break, and coastal domains, few details were available on their propagation or generation in nearshore areas such as the Elorn estuary.

The observed fortnightly variations in seiches in the upper Elorn estuary may therefore be associated with additional processes, including the role played by the estuarine stratification. However, the tendency for fortnightly seiches variations may also be partly associated with the evolution of the bathymetry in relation to the bottom slope break identified at around 5.5 km from the entrance of the city of Landerneau. Thus, as exhibited in previous Section 4.1, the upper Elorn estuary may behave as a "quarter-wave" resonator, leading to pronounced seiches variations in Landerneau. We suggested that these processes may be modulated by the tidal range being fostered during neap tides and lowered during spring tides. Indeed, in comparison to spring tides, neap tides with reduced water levels at high tides may result in an increased influence of the bottom slope break, accentuating the effect of the resonator played by the upper Elorn estuary. Characterized by reduced tidal ranges, neap tides also resulted in limited variations in the submerged surface around high tide. Neap conditions are thus likely to preserve resonator capabilities (in terms of geometric configuration) over a longer period of time of the tidal cycle than spring conditions, thus fostering the generation of an increased number of seiches oscillations. However, further investigations relying on the implementation of an advanced process-based physical model are naturally required to confirm these hypotheses. These advanced simulations may therefore integrate the variation of the bathymetry, including the locations of wetting-drying areas. It may furthermore be exploited to encompass a wide range of conditions leading to the generation of seiches in the upper Elorn estuary. Thus, beyond the tide-induced fortnightly variations in the free-surface elevation, this modeling may help to understand the superimposed effects of meteorological forcings and river discharges on estuarine hydrodynamic conditions [41,42].

The correlation of seiches characteristics with the tidal coefficient finally shows that important oscillations may also be reached during mean tides (tidal coefficient around 70) with heights liable to exceed 0.9 m (Figure 12). This suggested the influence of additional exciting sources, including especially meteorological conditions such as wind or atmospheric pressure events. An advanced analysis of seiches oscillations was thus conducted in Section 4.3 to discriminate between these different exciting sources.

4.3. Relationship with Meteorological Data

The potential relationship between seiches oscillations and meteorological conditions in the upper Elorn estuary was first investigated by focusing on a series of events combining different tidal regimes (spring or neap tides) with varying wind velocity and atmospheric pressure. These local investigations were then complemented by a global analysis of the potential correlations between seiches characteristics and meteorological conditions over the whole measurement period.

The detailed investigation of measurements collected at point #2 exhibited increased seiches oscillations in periods with strong variations in meteorological conditions. To illustrate these variations, we considered a series of events by focusing on the variations in seiches oscillations with respect to the variations in (i) the wind velocity amplitude at 10 m above the bed and (ii) the atmospheric pressure at sea level (Figures 13–15). Confirming the investigation conducted in Section 4.2, the influence of meteorological conditions on seiches oscillations appeared particularly noticeable during neap tides. Such variations were exhibited during neap tidal conditions in December 2017 (Figure 13). During this measurement period, the height and number of seiches oscillations around high tide were found to increase with the wind velocity. We thus obtained noticeable seiches oscillations at the beginning and end of the measurement period, characterized by wind velocity over 5 m s^{-1}. However, in spite of similar meteorological conditions in terms of wind velocity and atmospheric pressure, seiches oscillations were reduced during the spring tide of January 2018 (Figure 14). Such a comparison is consistent with the analysis conducted in the previous section, which exhibited an increased sensitivity of seiches oscillations to meteorological conditions during a neap tide. It also confirmed a series of investigations about the prevailing influence of wind variability on seiches-like motions [9,20,21,43]. Thus, by exploiting high-frequency measurements of sea level on the eastern coasts of the Aegen Sea (eastern Mediterranean), Alpar and Yüce [9] showed that the variability of the free-surface oscillations was mainly associated with wind variability, whereas longer-period variations (over 12 days) were mainly linked to variations in barometric pressure. More recently, by combining local measurements with process-based physical predictions obtained by a numerical model, Niedda and Greppi [20] assessed the influence of the strength and variability in the wind field on seiches within the Calich lagoon (western Mediterranean, Sardinia, Italy).

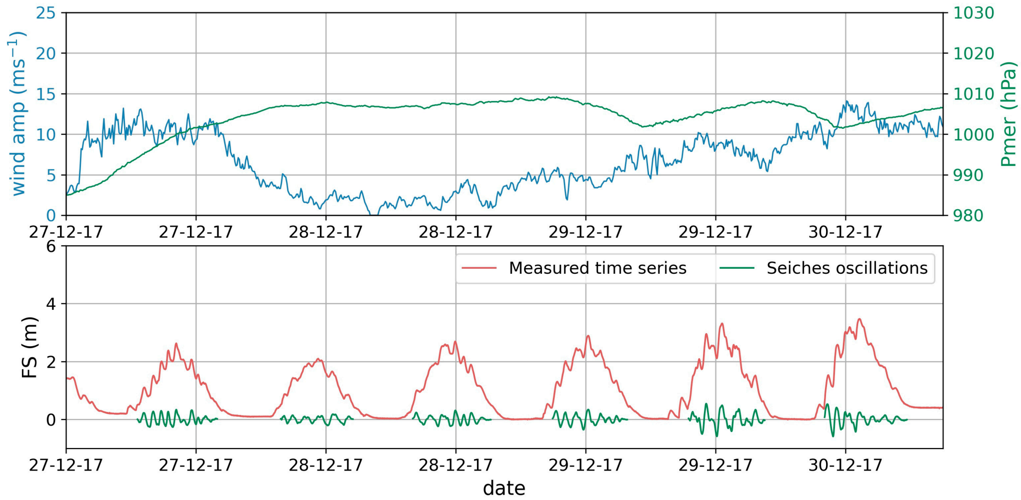

Figure 13. Time series of (**top**) the amplitude of the wind velocity at 10 m above the bed and the atmospheric pressure at sea level and (**bottom**) the observed free-surface (FS) elevation and difference between initial and smoothed FS at point #2 during neap tidal conditions in December 2017.

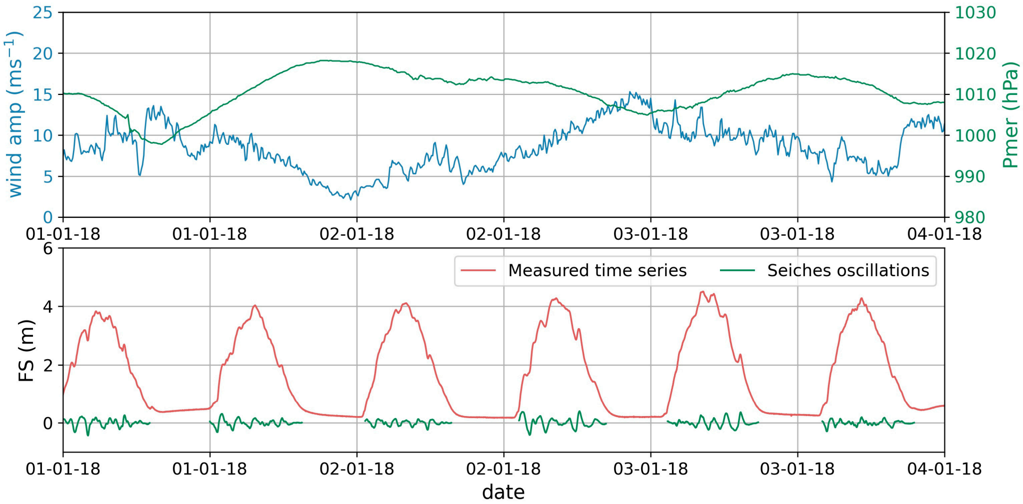

Figure 14. Time series of (**top**) the amplitude of the wind velocity at 10 m above the bed and the atmospheric pressure at sea level and (**bottom**) the observed free-surface (FS) elevation and difference between initial and smoothed FS at point #2 during spring tidal conditions in January 2018.

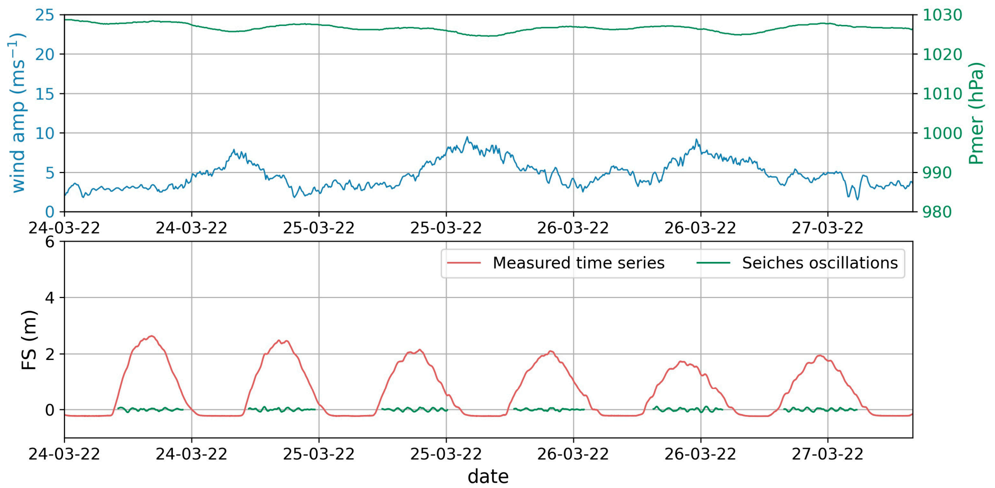

Figure 15. Time series of (**top**) the amplitude of the wind velocity at 10 m above the bed and the atmospheric pressure at sea level and (**bottom**) the observed free-surface (FS) elevation and difference between initial and smoothed FS at point #2 during neap tidal conditions in March 2022.

The detailed analysis of observed time series suggested furthermore that increased seiches oscillations were obtained in periods with reduced atmospheric pressure. These differences were exhibited by comparing two neap tidal periods characterized by contrasting values of the atmospheric pressure: The first one in December 2017 with pressure values below 1010 hPa and the second one in March 2022 with values over 1020 hPa (Figures 13 and 15). Thus, for wind velocity amplitude in the range 5–10 ms^{-1}, we clearly obtained more important seiches oscillations for low (Figure 13) than high atmospheric pressure values (Figure 15). Beyond the sole effects of atmospheric pressure and local wind direction on sea level variations, this suggests remote influences of meteorological conditions, including especially a heterogeneous spatial distribution of the wind velocity amplitude. Indeed, anticyclonic events with meteorologically quiet conditions develop around a central region of high atmospheric pressure, whereas cyclonic events characterized by storm episodes and more intense wind variations appear around a central region of low atmospheric pressure. Low atmospheric pressure values may thus reveal cyclonic events with stronger variations in the wind velocity amplitude than captured at the local meteorological station.

However, these different events shown in Figures 13–15 refer to specific conditions that may not encompass the sensitivity of seiches to meteorologically exciting sources over the five-year measurement period between 2017 and 2022. To assess this relationship, we evaluated the evolution of seiches characteristics (i.e., the mean height and number of oscillations per tidal cycle) with respect to the averaged atmospheric pressure and wind velocity amplitude around these different tidal cycles (Figure 16). These two averaged values are derived from observed time series collected at the meteorological station of Guipavas (Section 3.1.2) over a period of 12 h centered around peak maxima of smoothed variations in the free surface elevation. This period of 12 h was retained as being consistent with the averaged tidal period between two low tides in the Elorn estuary. In order to exhibit the sensitivity of seiches to meteorological conditions, particularly noticeable during neap tide, the analysis was conducted for tidal coefficients below 70 and seiches oscillations with averaged heights over 0.20 m. Contrary to seiches heights, the number of seiches oscillations per tidal cycle appeared to be correlated with the evolution of the averaged atmospheric pressure. Thus, seiches with the highest number of oscillations per tidal cycle (over 8) were mainly identified for low-pressure events with values below 1010 hPa. For these atmospheric conditions, we also noticed a slight tendency for an increased number of oscillations with the wind velocity amplitude. Beyond confirming increased sensitivity of seiches during low pressure events typical of cyclonic conditions, these results also exhibited that meteorological patterns were strongly influencing the number of seiches oscillations per tidal cycle during neap tidal conditions in the upper Elorn estuary. We therefore suggest that cyclonic events increase the range of exposure of the Elorn estuary to wind conditions varying in amplitude, direction, and timescales. Such conditions may thus foster the resonance of the estuary with external exciting sources and the generation of seiches oscillations. However, further investigations relying on an extending range of data are still required to characterize the evolution of seiches, focusing on their heights, in this estuarine environment.

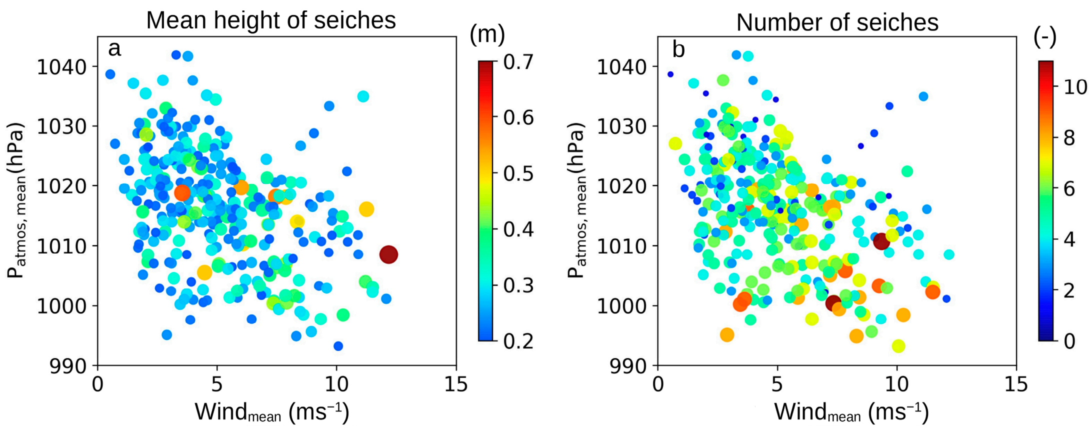

Figure 16. Correlation between (**a**) the mean height and (**b**) the number of seiches oscillations per tidal cycle (for tidal coefficients below 70 and mean heights over 0.20 m) with the averaged atmospheric pressure at sea level and the averaged amplitude of the wind velocity. These two parameters were computed for the different tidal cycles over a period of 12 h centered around peak maxima of smoothed variations in the free-surface elevation.

5. Conclusions

Different five-year measurement time series of the free-surface elevation were exploited and analyzed to characterize seiches oscillations in the upper part of a macro-tidal estuary subjected to a wide range of meteorological conditions, including especially varying wind velocities. This investigation was conducted in the Elorn estuary (western Brittany, France), focusing on the city of Landerneau, which is regularly subjected to river overflow and inundation events. As measurement points were located in wetting-drying areas, recorded time series were highly discontinuous around low tides. An original data analysis technique was thus implemented to characterize seiches oscillations around high tide. This analysis technique was applied and exploited to exhibit the potential relationship between (i) seiches characteristics—including the averaged height and number of oscillations per measured tidal cycle—and (ii) tidal and meteorological conditions. The main outcomes of the present investigation are as follows:

1. Seiches oscillations were mainly identified in the upper part of the Elorn estuary, around high tide, with heights liable to exceed 0.6 m and apparent periods of around 45–70 min in the city of Landerneau.
2. The estuarine bathymetry is characterized by a bottom slope break at around 5.5 km from the entrance of the city, which may explain a part of seiches oscillations. Thus, it was suggested that the upper estuary was operating as a "quarter-wave" resonator, increasing short-period oscillations such as seiches.
3. Seiches were characterized by a fortnightly periodicity with a tendency for an increased number of oscillations and associated heights liable to exceed 0.8 m during neap tides. A clear contrast was, however, exhibited between (i) our investigation in a nearshore estuarine environment and (ii) previous studies that exhibited such neap-spring variations in seiches oscillations in coastal open locations, seemingly attributed to tide-generated internal waves from distant sources (typically the shelf break).

4. Fortnightly seiches variations appeared further disturbed by additional exciting sources, including especially the effects of meteorological conditions. Thus, we obtained an increased number of oscillations in strong wind conditions.
5. These effects were particularly noticeable in low atmospheric pressure regimes, suggesting that cyclonic events were propitious to the occurrence of seiches in this estuarine environment.

The upper Elorn estuary is, therefore, a shallow-water environment regularly subjected to strong seiches oscillations superimposed on tide-induced variations in the free-surface elevation. Long-term measurements acquired in this location provided further insights about the influence of tidal and meteorological sources. However, the characterization of seiches still requires further investigation in this environment subjected to complex interactions between estuarine hydrodynamic processes and external forcings. The analysis of extensive measurements, including different meteorological stations, may naturally help to confirm and exhibit seiches characteristics and the different influences of exciting sources. However, the greatest expectation lies in the implementation of a process-based physical computer model liable to reproduce seiches oscillations in the upper estuary. This numerical model may thus help to assess the role of large-scale wind variations on the development of seiches. It may also be exploited to understand if internal waves associated with stratification effects within the estuary can contribute to seiches oscillations by converting a significant part of their energy into surface waves. Beyond a refined characterization of seiches potentially useful for broader applications, such advanced investigations will finally provide further insights about the dynamic of water level variation triggering inundation events in the city of Landerneau.

Author Contributions: N.G.: conceptualization, methodology, software, validation, formal analysis, investigation, writing—original draft, writing—review and editing, visualization, supervision, and project administration; G.C.: writing—review and editing, and project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors thank Olivier Boucher and Antoine Douchin (Cerema) for their technical support in setting up the instrumentation system in the city of Landerneau.

Conflicts of Interest: The authors declare no conflicts of interest.

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