Data sets characterizing tide and current fluxes in coastal basins

Elvira Armenio[1], Francesca De Serio[1], Michele Mossa[1]

[1]Department of Civil, Environmental, Building Engineering and Chemistry, Technical University of Bari, Via Orabona 4, 70125 Bari, Italy

5 *Correspondence to*: Elvira Armenio (elvira.armenio@poliba.it)

Abstract

Understanding the hydrodynamics in a coastal site has always been fundamental and preliminary to any management and decision-making plan, because of its role played in many correlated physical processes, such as sediment transport or spreading of pollutants. Therefore, many monitoring programmes have been commissioned to investigate *in situ*
10 hydrodynamic patterns, even if often limited in time or space. The principal consequence of these campaigns is a large and growing amount of data provided by marine sensors, gathered in coastal data sets. The key point is the necessity to transform data into information for users, so that data sets could be not simple repositories, but a source to provide more insights on specific coastal trends. The aim of the present paper is to outline a simple, generic and not site-specific framework, made up of i) a sequence of analyses on data and ii) the assessment of some indicators of the principal coastal
15 processes in the target basin. This procedure requires high quality measurements and simple but robust methods of analysis to identify variable correlations and trends with low computational cost. To demonstrate how it could be applied, a case study is presented, referring to the Mar Piccolo, a shallow water basin located in the inner part of the Ionian Sea (Southern Italy). The detailed measurements were processed in time and frequency domain and the following indicators were identified: the net flow through a connecting channel, the time delay of current peaks between upper and bottom
20 layers, the ratio of peak ebb and peak flood currents, the tidal asymmetry factor. Their assessment offered results on the vertical structure of the flow, on the correlation between currents and tide, on flood/ebb dominance. Therefore, the principal outcome of this paper is to show that adopting such a simple and general framework allows us to capture typical hydrodynamic and recurring features of a coastal setting.

25 **Keywords:** field data set; analysis in time domain; analysis in frequency domain; net flux; tidal asymmetry.

1 Introduction

A thorough knowledge of the hydrodynamic characteristics of a coastal site is the prime basis of any study dealing with the transport of sediments, the diffusion of polluting tracers and degradation of water quality (De Serio and Mossa, 2016a; 2016b), the interaction with marine and submarine structures, the coastal adaptation to climate changes. Thus, it results
30 fundamental and preliminary to any management and decision-making plan. For this reason, in the last decade, many monitoring programmes and projects have been commissioned to investigate *in situ* hydrodynamic trends and patterns, by means of the deployment of suitable sensors specifically dedicated. In any way, requiring these instruments expensive running and maintenance, their functioning is often set *ad hoc*, i.e. is limited to the project duration. In other cases, *in situ* and real-time monitoring is driven by the necessity to provide rapid and tangible responses to urgent problems that the
35 community must face, such as accidental outflow and spreading of pollutants, so that data is acquired for time periods of

few days during surveys carried out along specific routes in confined sea areas. The principal consequence of this policy of intervention is a large and growing amount of assessed data, gathered in coastal data sets.

Regardless of user demands, it is an established fact the diversity and density of data from marine sensors and measuring instruments. Henceforth, the key point is the necessity to convert with specific tools data into information. In this way, users may learn from data, not intended as a simple repository. Further, observatory systems do not always communicate data in readily useable information for those needing to make the decisions (Hipsey et al., 2015). As an example, flood or ebb tidal dominance in a coastal setting could induce peaks of current velocities and thus control the direction and magnitude of net landward or seaward water fluxes and hence the sediment transport (Brown and Davies, 2007). To communicate to stakeholders that a coastal system is experiencing accretion or erosion it may be more effective to present a morphodynamics map rather than time series of tidal elevations. Consequently, it is fundamental the choice of tools and methods to adopt in order to optimize the knowledge deriving from acquired data, according to the interested party's priorities. Specifically, raw data could be processed and interpreted by means of: i) numerical modelling; ii) empirical analysis, i.e. data driven approach (DDA).

Most of the numerical models used in predictive operational oceanography allow to reproduce and predict the hydrodynamic processes, considering regional, sub-regional and coastal scales, but do not reach spatial resolutions lower than a few hundred meters (Samaras et al., 2016). Consequently, difficulties are encountered when typical features of coastal engineering should be studied at local scale. Reliable modelling systems that can scale down from the ocean to the coastal scale have emerged as a need and the recent tendency is to develop multiscale modelling systems, based on a multiple-nesting approach (Samaras et al., 2016). All these models have to face three heavy limitations to provide reliable results. Firstly, they need a setup, a calibration and a validation, so that their integration with waves, current and tide data is fundamental (De Serio et al. 2007; De Serio and Mossa, 2014). Secondly, the accuracy of model outputs relies on the quantity, quality and duration of the available observations, which are often characterized by a poor resolution in time and space, because intermittent or too sparsely sampled. Consequently, extensive field measurements are still strongly necessary and monitoring actions should be rationally programmed (De Serio et al., 2015; Sauvageta et al., 2000; Benque' at al., 1982). More diverse and high-resolution observations create advantages for testing the rigor of models at scales relevant to the dominant underlying processes (Hipsey et al., 2015). Thirdly, numerical models are often overly complex, which is not an assurance of their ability to better capture the hydrodynamics of the costal system, and the modelled variables should be suitably translated into metrics required by catchment communities.

Referring to DDA, it has been in use for nearly three decades for hydrological modelling, prediction, and forecasting (Elshorbagy, 2010a; 2010b). In ocean and coastal research community, the origins of DDA are difficult to identify but evolved from the application of statistical analysis techniques and a recognition that many coastal data sets seem to exhibit coherent patterns of temporal behavior that could be used to characterize physical processes. In addition, they could be extrapolated to form a prediction of a future coastal state (Reeve et al., 2016). In this sense, the described approach has gained the epithet data-driven, because, when properly analysed and processed, field data drive the successive step of forecasting. The availability of extensive data sets has stimulated a rapid expansion in the type and sophistication of statistical methods used for DDA (Reeve et al., 2016). As an example, a DDA based on the application of singular spectrum analysis was used to trace forced and self-organized components of shoreline change (Różyński et al., 2001). Principal oscillation patterns were used to derive a data driven model of changes in nearshore bathymetry by Różyński and Jansen (2002). Różyński and Lin (2015) investigated on beach equilibrium profile of cross shore seabed records by the application of a cross-correlation analysis. The link between DDA and process understanding is not a one-way relationship. The knowledge and insights obtained by analyzing extensive coastal measurements can be used to reveal

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links between data sets of two or more different variables. For example, Horrillo-Caraballo and Reeve (2008) applied a DDA based on a cross-correlation analysis to correlate beach profile and wave measurements. They demonstrated that if it is possible to establish a link between the hydrodynamics and the beach morphology then this, together with hydrodynamic forecasts, might be used as an effective predictor of coastal morphology.

Rather than providing some forecasting instruments, the aim of this paper is to outline a simple strategy, which is based on a fundamental requisite, following Różyński, et al. (2001) and Reeve et al. (2016), i.e. data sets generated from high quality field measurements encapsulate the whole information regarding spatial and temporal patterns of the physical processes that take place in the coastal zone. Therefore, the analysis of a sequence of measurements of forcing variables, ensuring a suitable spatial and temporal resolution, allows to find evidence of trends, cycles, coherent patterns or other smoothly varying modes of change (Reeve et al., 2016). In this way, coastal monitoring programmes would provide a major source of scientific insights, because starting from historic data extracted from extensive field measurements allow us to advance our understanding on the principal recurrent physical processes acting in that coastal environment.

Our purpose is to delineate an agile learning framework, constituted by sequential operations on data sets and successive deductions of some coastal state indicators. Thus, it would be possible to detect some recurring patterns and trends emerging from an observational work. Based on an appropriate extrapolation, making predictions of future patterns of behaviour could be the successive step, also in conjunction and integration with numerical modelling, but this is not an objective of the present study.

The first requirement to arrange for the above written framework is the availability of high quality data, derived from extensive monitoring campaigns. They should include measurements acquired simultaneously and on small spatial scales, with a proper sampling frequency and for a continuous and sufficiently long timeframe to capture seasonal or even annual typical features in the investigated site. If the investigated scenario is subjected to modifications, understanding trends is possible only if such changes have been captured in the measurement records. It is worth noting that field information of high quality is not only demanded by numerical models tuning, running and validating.

The second requisite is the application of simple and robust methods of analysis to identify variable correlations and trends with low computational cost. An example are the analyses of Aubrey and Emery (1985), Solow (1987) and Ding et al. (2001) of data from long-established national tide-gauge networks, used for tidal harmonic decomposition and surge analysis.

The framework here outlined is made up of the following stages, based on the availability of wave, tide and current data: (i) a preliminary inspection on the assessed tidal data with the spectral analysis, allowing to filter out spurious signals; (ii) the analysis of temporal trends and variability of hourly-averaged vertical profiles of the current, extracted for selected phases along the tidal period; (iii) the spectral analyses of tide levels and water currents measured at different depths, in order to find possible correlations; (iv) the computation of the tidal asymmetry factor; (v) the harmonic analysis of the tidal constituents, to identify spatial and/or temporal asymmetry and flood or ebb dominance; (vi) the identification of some state indicators, which are quantitative parameters providing more insights on specific behaviours of the coastal basin.

As evident, such a framework is generic, replicable and not site-specific. To demonstrate how it could be employed, a case study is presented and discussed. We illustrate the application of this procedure to a target area in Southern Italy, considered highly vulnerable, being exposed to heavy urban and industrial pressure, so that its safeguard is one of the main aims of the local environmental policy. Therefore, a continuous monitoring action of the principal hydrodynamic parameters in this site, by means of proper sensors, is considered a useful managing tool, in terms of planning and prevention along with intervention when some accidental spills occur. The hydrodynamic circulation in this area has been

investigated in literature generally by means of numerical modelling and mainly considering the system as governed by the wind and the tidal forcing (De Serio et al., 2007; Scroccaro et al., 2004; Umgiesser et al., 2007). Still few studies (De Serio and Mossa, 2015; 2016a; 2016b) have started to examine large on site data sets, but they concerned above all the area outside the basin. The present study examines novel data assessed in a monitoring station close to the inner basin.

5   The investigated period refers to the last autumn-winter season (01.10.2015 ÷ 31.12.2015), due to the start-up and working properly of the measuring system.

The paper is structured as follows. In section 2 the target site and the adopted procedures to measure and process data are described. ==Section 3 displays the principal findings, the data correlation and the recurring trends. Finally, section 4 discusses about the derived indicators and the applicability limits of this procedure.==

10   **2 Materials and methods**

2.1 Study site and data sources

The proposed ==framework== is applied to a target area, i.e. a shallow water basin named Mar Piccolo and located in the inner part of the Ionian Sea (Fig.1a). It is composed by two bays, respectively named I Bay and II Bay. Its total surface is about 21.7 km^2, its maximum depth is around 15m in the I Bay and 10m in the II Bay (De Serio and Mossa, 2016b; De Pascalis

15   et al., 2015). It is joined to Mar Grande, an external basin, by means of an artificial channel, i.e., the Navigable Channel, and a natural one, i.e., the Porta Napoli Channel (Fig.1b). The Navigable Channel is 58m wide, 375m length and 14m deep, while the Porta Napoli Channel is 150m wide and 2.5m depth. With regards to these dimensions, its hydrodynamic patterns could be properly studied only on a local scale.

During May 2014, a monitoring station was installed in the Navigable Channel (Fig. 1). The geographical coordinates of

20   Station A are 40.473° N and 17.235° E and its local depth is on average 13.7m. The station is equipped with a bottom mounted ADCP and a wave array, both by Teledyne RD. The acoustic frequency of the ADCP is 600KHz and the velocity accuracy is 0.3% of the water velocity ±0.003m/s. The ADCP is bottom mounted, upward facing and has a pressure sensor for measuring mean water depth. The transducer head is at 0.50m above the seafloor. Velocities are sampled along the water column with 0.50 m vertical bin resolution and a 1.60 m blanking distance. The water column is therefore

25   investigated from a distance from the sea bottom of 2.1m up to the most superficial bin not biased by waves. The surface layer, with a thickness on average equal to 1.5 m, is excluded from the analysis.

Starting from June 2014, mean current velocity profiles have been collected continuously at 1 hour intervals, using an average of 60 measurements acquired every 10s. In this way, hourly averaged velocity components along the water column are provided. Analogously, hourly values of significant wave height Hs have been acquired.

30   On August 2015, an ultrasonic tide gauge (by General Acoustics) was settled in the Navigable Channel at Station B (Figure 1b). It is a stand-alone water level gauge, whose probe records and calculates the time that an acoustic pulse employs to be reflected vertically on the sea surface. The ultrasonic tide gauge is installed on a swinging bridge crossing the channel, named S. Francesco di Paola. Starting from September 2015, hourly values of tide levels have been acquiring with a sampling rate of 5Hz, while the gauge resolution is of 1 mm and its accuracy is of ±0.01m.

35   In addition, five accelerometer sensors were considered in the present analysis. The sampling rate of these sensors was 1000Hz and they were placed in the centreline of the bridge S. Francesco di Paola.

2.2 Data processing and identification of indicators

As previously written, the framework outlined in this paper is made up of i) a sequence of analyses carried out on the data records of wave heights, tidal levels and current velocity components, both in time and frequency domain, ii) the successive identification of some parameters which could explain the hydrodynamic behaviour in the basin, especially referring to cyclic trends. About the first aspect, field measurements were examined and managed following the steps further detailed.

A preliminary evaluation of the reliability of data recorded by the ultrasonic tide gauge was carried out with the spectral analysis. To evaluate the possible correlations between the measured currents flowing in the channel and the tidal records, the vertical profiles of current velocities were extracted for selected phases along the tidal period. The Fast Fourier Transform (FFT) algorithm was used to relate tidal and current data at different water depth. Successively, tidal asymmetry was analysed applying two different approaches to identify spatial and/or temporal asymmetry and flood or ebb dominance. Finally, considering that in shallow coastal waters and tidal inlets, energy from the dominant fundamental tidal constituents is non-linearly transferred through processes including advection, finite-amplitude effects and friction, generating higher harmonic overtides and compound tides, a harmonic analysis was conducted on the tidal signal (Aubrey and Speer, 1985; Speer and Aubrey, 1985; Di Lorenzo, 1988; van de Kreeke, 1988; Westerink et al., 1988; Le Provost, 1991; Fortunato and Oliveira, 2004). In this way, the relationship between the $M2$ (astronomical constituent) and the $M4$ (shallow-water constituent) amplitude and phase, commonly used in identifying the nature of the tide or tidal current asymmetry, was investigated (Boon and Byrne, 1981; Friedrichs and Aubrey, 1988).

As specified in the following paragraphs, these analyses allowed us to deduce and estimate some useful indicators of the basin behaviour, such as the net flow along the channel, the time delay in vertically spreading of water mass, the peak ebb-peak flood ratio and the tidal asymmetry factor.

2.2.1 Analysis of recorded tide and wave data

Tidal data were first examined to assess the reliability of the used ultrasonic tide gauge in Station B. Once blanks were removed, the data were checked and were promptly compared with the tide levels recorded at Station St. Eligio (Fig. 1) and managed by the national tide gauge network of the Italian Institute for Environmental Protection and Research (ISPRA). The time frame used as reference period was 01.10.2015 ÷ 31.12.2015. Station St. Eligio is located outside the Mar Piccolo at geographical coordinates 40° 28 '32.17"N and 17° 13' 25.55"E at a distance of about 700m from Station B (Fig. 1).

Firstly, the FFT technique was applied to process the tidal data recorded from both Station B and Station St. Eligio, thus allowing a comparison of their amplitude spectra in the frequency domain. Successively, a further analysis was carried out, considering that for technical reason the ultrasonic tide gauge is set on the swinging bridge crossing the Navigable Channel, subjected to intense and heavy road traffic. The traffic-induced vibrations should not influence the tide gauge measurements, since the tidal record and bridge vibration frequencies are expected to be in completely different ranges. Nevertheless, since the gauge metallic support is clamped to the bridge structure, possible displacements could be amplified, inducing some disturbances on the tidal signal as a consequence. Therefore, in a cautionary perspective, an analysis of the tidal and bridge vibration signals was carried out in the frequency domain. The bridge vibrations were investigated by processing the field data provided from five accelerometer sensors installed on the bridge and available for the day 08.10.2012. Two data sets were examined, referring to a duration time of 300 seconds each. The first spanned a time window from 12:54 a.m. to 12:59 a.m. and the second from 03.06 p.m. to 03:11 p.m. These two samples were taken into account because representative of an intense and a light traffic conditions, respectively.

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The time series of the acceleration records were processed by means of a double numerical integration using the trapezoid method. With this procedure, the time series of the bridge vibrations were computed.

For sake of completeness, the time series of the measured significant wave heights H_s acquired in Station B, provided with a wave meter and a processed by a module for real-time collection of hourly wave data, were also examined for the same reference time window.

2.2.2 Analysis of recorded sea current data

The hourly-averaged vertical profiles of the current velocities recorded in Station A of the Navigable Channel (Fig. 1b) were analysed for the reference period, displaying trends which highlight a variable structure of the flow along the water depth.

For the successive analysis, the current velocities in the horizontal plane, originally measured along E-W and N-S directions respectively, were managed by a plane rotation of the coordinate system, to get their components along the transversal and longitudinal channel axis, which is 12° clockwise rotated from N (Fig. 2). Conventionally, the longitudinal velocity components v are positive if entering towards the Mar Piccolo, while the transversal velocity components u are positive if directed to the eastern bank of the channel.

Based on the available topographic data, the cross section of the Navigable Channel was deduced and the net flows through the Navigable Channel were estimated for the investigated period, considering that the transversal u velocities could be disregarded in this computation. In this way, it was approximated that the flow was quasi 2D in the longitudinal-vertical plane of the channel. The monthly-averaged longitudinal current velocities were evaluated for each depth cell of the ADCP and multiplied by the corresponding sub-section of the channel itself.

2.2.3. Analysis of recorded tide

Firstly, it was considered that in the entrance to a bay or strait (as for the case of the Navigable Channel), the tidal current is reversing, i.e. it flows alternately in approximately opposite directions with an instant or short period of little or no current, called slack water, occurring at each reversal. During the flow in each direction, the current velocity varies from zero, at the time of slack water, to a maximum, called flood or ebb, about midway between the slacks (Brown et al., 2007; Dronkers, 1986; Dronkers, 1998). To investigate on the reversing tidal current in the Navigable Channel, the time series of the tide was overlapped to the time series of the longitudinal current velocity at various depths.

Successively, the asymmetry of the tidal current was examined. This is a common phenomenon in tidal inlets and plays an important role in sediment transport processes and pollutions spreading within the inlet. Tidal asymmetry can be flood or ebb dominant and it can be spatial and/or temporal (Dronkers, 1986). Flood dominant asymmetry occurs when the flood current is stronger than the ebb current, while ebb dominant asymmetry occurs in the opposite situation (Jewell et al., 2015, Nidzieko, 2010). As indicator of ebb or flood dominance, the ratio R of peak ebb current and peak flood current was computed for the present case and for the reference period. Consequently, the ebb dominance condition is characterized by $R \geq 1$; on the contrary, the flood dominance condition by $R \leq 1$. To investigate on the tidal spatial asymmetry, i.e. on the tidal asymmetry near the bottom, at intermediate depth and at the surface, the ratio R was computed at the investigated depths, for two consecutive ebb and flood currents.

Also, the inequality in the temporal durations of successive ebb and flood phases was considered as a further condition to identify temporal asymmetry. Tidal asymmetry was thus indicated by a disparity between the number of ebb and flood current hours in the time series.

The application of a tidal asymmetry factor γ proposed by Dronkers (1998) was also used as an additional approach to investigate on tidal asymmetry. Referring to the study conducted by Townend (2005), Townend et al. (2000), Friedrichs and Aubrey (1988) and Aubrey and Speer (1985) for different inlets and estuaries with a triangular cross-section shape, it was demonstrated that the tidal asymmetry factor can be expressed as:

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$$\gamma \propto \left[\frac{h+a}{h-a}\right]^2 \frac{S_{LW}}{S_{HW}} \approx \left(1 + 2\frac{a}{h}\right)\left(\frac{\frac{v_c}{h}\left(1-\frac{a}{h}\right)}{\frac{v_c}{h}+\frac{v_s}{a}}\right) + O\left(\frac{a}{h}\right)^2 = \frac{\left(1+\frac{a}{h}\right)}{\left(1+\frac{v_s}{\frac{v_c}{h}}\right)} \tag{1}$$

where a is the amplitude of the tidal range, h is the mean water depth, v_s is the volume of the intertidal storage (i.e. the volume between low water and high water over intertidal areas), v_c is the volume of the channel (i.e. the volume of the

10   channel delimited by the mean tide level), S_{LW} and S_{HW} are the surface at low and high tide, respectively.

A value of γ equal to one suggests a uniform tide characterized by equal duration of ebb and flood currents, so that the tide is symmetrical. The condition $\gamma > 1$ results in flood-asymmetry (long slow ebb and short fast flood), while the condition $\gamma < 1$ results in ebb-asymmetry (long slow flood and short fast ebb).

To have a further confirmation of the abovementioned results, the least-squares harmonic analysis of the signal acquired

15   in Station B was computed, using the Matlab T_Tide package (Pawlowicz et al., 2002). The results from the harmonic analyses were used to investigate the relation between the various shallow-water tidal constituents that might contribute to tidal asymmetry. The tidal regime in the study area was furtherly identified by the evaluation of form number F, defined by Pugh (1987) as

20   $$F = \frac{O_1+K_1}{M_2+S_2}, \tag{2}$$

where $O1$ is the principal lunar diurnal, $K1$ is the lunisolar diurnal, $M2$ is the principal lunar semidiurnal and $K2$ is the principal solar semidiurnal. Considering eq. (2), the condition $0.25 \leq F < 1.5$ represents a mixed primarily semidiurnal tide characterized by two high and two low waters each tidal day, with relatively small differences in the respective highs

25   and lows.

In tidal inlets where semi-diurnal tides prevail, the dominant offshore forcing tide is the principal semi-diurnal lunar $M2$ tidal constituent, as in our case. The type of tidal asymmetry can be characterized by phase and amplitude relations between the $M2$ tide and its first harmonic, the shallow water $M4$ constituent (Boon and Byrne, 1981; Aubrey and Speer, 1985; Boon, 1988; Di Lorenzo, 1988; Friedrichs and Aubrey, 1988; Moore et al., 2009).

30   Aubrey and Speer (1985) showed that the phase difference, $2\theta_{M2} - \theta_{M4}$ where θ is the phase of the tidal height, determines whether an inlet is flood dominated or ebb dominated. A 90° phase difference of tidal height means shorter flood duration (compared with ebb duration). This results in a higher flood current velocity and consequently a flood dominant situation. A 270° phase difference of tidal height means longer flood duration, which can result in a higher ebb current velocity than flood current velocity. Aubrey and Speer (1985) and Friedrichs and Aubrey (1988) conducted

35   theoretical studies and fieldwork on tidal asymmetry for estuaries with semidiurnal tidal regime. Based on their studies, under a semidiurnal regime, an inlet has flood-dominant current if $0° < 2\theta_{M2} - \theta_{M4} < 180°$ and ebb-dominant current if $180° < 2\theta_{M2} - \theta_{M4} < 360°$.

3. Results

3.1 Tide and waves

The time series of tide levels assessed at Station B and Station St.Eligio show that the target area is characterized by a semidiurnal tide. The maximum tide level recorded in the investigated period at Station B was 0.45m, while the minimum was -0.25m. Applying the FFT algorithm, a general agreement is found between the two signals, which show the same peaks of amplitude at periods of 12h and 24h (Fig. 3a). The two data sets were also examined focusing on an extreme meteorological event, occurred on 16th October 2015, when during a storm the rainfall reached 0.191m in the city of Taranto in few hours during the morning. The time series of both Stations (Fig. 3b) display very similar trends of the recorded tidal levels, except than in a short time window (around 12:30 am), when consistently the outflow from Mar Piccolo flowing through the Navigable Channel increased due to the rainfall contribution, thus inducing a depth in Station B higher (about twice) than in Station St. Eligio. This behaviour highlights the trend of Mar Piccolo to act as a sort of catchment basin.

From the analysis of bridge vibration, for the sake of brevity, referring to only one of the five accelerometer sensors, Figure 4a shows the time series of the calculated vibrations in the case of intense traffic condition. Similar trends and values were detected also referring to the other accelerometers. Measured accelerations are in the range 12-16m/s^2 and the deduced vibrations are less than 10^{-3}m in all cases. Using the FFT algorithm, the amplitude spectra of the bridge vibrations were obtained (Fig. 4b). The highest amplitudes are found in the frequency range of 2-2.5Hz as evident from the enlargement of Figure 4c. A prompt comparison of the amplitude spectra of tide level (Fig. 3a) and bridge vibrations (Fig. 4c) proves experimentally the expected results, i.e. the frequencies typical of the two signals are in different ranges, without any overlap.

Figure 5 shows the time series of the significant wave heights in the investigated period. The greatest value of observed H_s is equal to 0.8m, while the average value of H_s is around 0.3m. These values are consistent with the H_s data recorded in Mar Grande and shown in Armenio et al. (2016), which showed for the same season a maximum value around 1.2m. In fact, we could expect that swell waves, entering the Mar Grande basin from its SW opening (Fig.1), propagate throughout finally reaching the Navigable Channel, where they arrive quite smoothed. The directions of the wave propagation in the Navigable Channel is generally confined to NNE/SSW due to the orientation of the channel itself (clockwise rotated of ~12° from N).

3.2 Currents

Figure 6 shows a stick plot of the hourly measured currents at z=-2.0m, z=-5.5m and z=-10.5m respectively, being z the vertical distance from the sea surface. It is evident that the current is mainly oriented along the N-S axis, driven by the longitudinal direction of the channel, at all the investigated depths. From the stick plot of Figure 6, it is evident that the longitudinal current components are greater than the transversal ones, thus disregarded in the following analysis.

The values of the longitudinal velocity components v due to an inflow towards the Mar Piccolo are plotted in Figure 7a, once monthly-averaged in the reference period of measurement. The incoming flow is characterized by velocities spanning from 0.2m/s at surface layers to 0.15m/s near the bottom. Smaller values (v around 0.12m/s) are observed near the surface for the month in November. Figure 7b displays the monthly-averaged velocities of the outflow from the Mar Piccolo, with absolute values greatest in the most superficial layers (v around -0.25m/s), then decreasing while approaching the bottom (v around -0.12m/s). The transversal current components u varies in the range -0.08m/s÷0.023m/s, being one order of magnitude smaller than the longitudinal ones, as expected because of the restraint action played by the

channel banks. Figure 8 illustrates the net flow across the Navigable Channel in the reference period, with positive sign referring to net flow entering toward the Mar Piccolo. At deeper layers, from the bottom up to $z=-4$m the net flow results inflowing, while in the most superficial layer it is directed outward of the basin. This resulting net flow agrees with a previous numerical modelling (De Pascalis et al., 2015), which represented the annual hydrodynamic simulation in this

5   site in the year 2013. Also, the annual field data by Armenio et al. (2016) and De Serio and Mossa (2015; 2016a) are consistent with these findings. In the abovementioned studies, a double circulation was observed in the channel, characterized by an annual-averaged predominant outflow in the superficial layer and, on the contrary, an annual-averaged predominant inflow near the bottom.

3.3 Tide reversing and asymmetry

10   To investigate on the reversing tidal current in the Navigable Channel, the time series of the tide was overlapped to the time series of the longitudinal current velocity at various depths. Specifically, we observed that during each tidal cycle, the trend of the current at different depths showed recurring features. Therefore, the phase averages of both tide elevation and current velocity were computed and are plotted in Figure 9, referring to surface ($z=-2$m, $z=-3.5$m), intermediate ($z=-6.5$m) and bottom layers ($z=-10.5$m). The use of the phase averaging procedure assured that the observed behaviour is

15   recurrent and Figure 9 can be considered representative of the investigated period. In Figure 9 the current flood peak in the surface layer ($z=-2.0$m) occurs at the same time of the high tide. At lower layers ($z=-3.5$m, $z=-6.5$m and $z=-10.5$m), there is a time lag of about two hours between the high tide and the flood current peak. In addition, it can be noticed a double-peaks flood current in the most superficial layers ($z=-2.0$m and $z=-3.5$m). This trend confirms Byun and Cho's conclusion (2016) for the case of a semidiurnal tide dominated basin.

20   If all the water in the Mar Piccolo was in dynamic equilibrium with the external Mar Grande, the current would be zero (slack waters) when the tidal level inverts, i.e. at low and high tides. On the contrary, Figure 9 shows that slack waters occur during the passage from high tide to low tide and vice-versa. Analysing the relationship between the instant times of high/low tide and the instant times of slack waters, the result is a progressive wave current. This means that the maximum flood and ebb occurs around the times of high and low tides, while slack waters occur in between. From the

25   observed data, there is a lag of about a two-three hours between the time of slack waters and the low or high tide levels. The findings about the tidal spatial asymmetry, i.e. on the tidal asymmetry near the bottom, at intermediate depth and at the surface, are summed up in Figure 10, where five examples representative of the trend in the reference period are illustrated, for the sake of brevity. In all the selected frames, at bottom layers $R \leq 1$ meaning flood stronger than ebb currents, on the contrary, at surface layers $R \geq 1$ meaning ebb stronger than flood current.

30   The tidal temporal asymmetry was also deduced, observing that the value of R varies in time at each water depth. As an example, Figure 11 shows the variability of R, computed as the ratio between the minimum and maximum current value for each day, referring to surface and bottom layers in November 2015. Again, a predominance of flood currents in deeper layers is noted, with prevailing values of $R<1$, as well as a predominance of ebb currents in surface layers is obtained, with prevailing values of $R>1$.

35   The inequality in the temporal durations of successive ebb and flood phases showed that the number of ebb currents hours is greater than that of flood currents at surface layers. Long and stronger ebb and short and slower flood currents were identified. On the contrary, at bottom layers, flood currents duration prevails over ebb currents duration. Long and stronger flood currents with short and fast ebb currents were detected. At intermediate depths, comparable duration of flood and ebb currents was found. For the sake of brevity, as an example, Figure 12 shows the temporal duration of flood and ebb

40   currents at $z=-2.0$m, $z=-6.0$m and $z=-11.5$m for a selected short period.

The tidal asymmetry factor γ was also computed following eq. (1). A trapezoidal cross section with 25° sloped lateral sides was assumed for the Navigable Channel, based on the available and historical bathymetric data. The tidal amplitude a was considered equal to the average of the observations and the mean depth h was set equal to the local depth in Station B. The factor results γ =1.1. According to Dronkers (1998), it denotes an overall prevailing of light flood dominance condition, furtherly confirming previous analysis.

Figure 13 shows the results of the harmonic analysis of the signal acquired in Station B, i.e. the amplitude and frequency of the main tidal constituents. Table 1 lists the constituents' phase. The semidiurnal $M2$ constituent is the dominant component of the tidal regime observed at the Mar Piccolo basin, with an amplitude value of 0.044 m. Further main constituents are $S2$, $N2$, $L2$ and $K1$. As already highlighted from the FFT analysis, in the basin the tidal movement is the main driving force for the horizontal water flow.

Applying Eq.2 for the present case study and referring to data of Figure 13 and Table 1, the form number F is equal to 0.726, which corresponds to a semidiurnal regime, as expected.

The primary source of asymmetry in the Mar Piccolo, governed by a semidiurnal tidal regime, is the interaction of the principal lunar semidiurnal tide $M2$ with its first overtide, the lunar quarter diurnal $M4$, as also reported in similar case studies (Aubrey and Speer, 1985; Van de Kreeke and Robaczemska, 1993).

Finally, referring to phase values in Table 1, the calculated phase difference $2\theta_{M2} - \theta_{M4}$ by Aubrey and Speer (1985) is equal to about 145°, furtherly confirming the flood dominant conditions already highlighted.

3.4 Tide and currents correlation

The adopted approach, based on an analysis in time and frequency domains, proved that the flow current along the Navigable Channel has a vertical structure connected and varying with the tide phase, specifically characterized by a cyclic trend. As well, on the seasonal period, the Mar Piccolo basin resulted dominated by a semidiurnal tide regime, with a predominance of flood currents, above all in deeper layers. To extrapolate these results and trying to provide a practical prediction scenario, the possible correlations between the longitudinal currents in the channel and the tidal records were investigated. Firstly, in qualitative terms, the vertical profiles of the longitudinal current velocity v, assessed at Station A, were analysed at four selected phases for each tidal cycle: tide crest, passage from crest to trough, tide trough and passage from trough to crest. For the sake of brevity, only four profiles are shown (Figs. 14a÷d), referring to successive steps in sequence, chosen as representative of the whole period. Analogous behaviours in fact were noted during all the other tide cycles.

Figure 14a shows the vertical trend of the longitudinal current velocity corresponding to the passage from trough to crest (15.11.2015, hour 23:00). In this case, the flow is directed towards the Mar Grande near the surface and reverses at about 3m depth, being directed towards the Mar Piccolo from this depth to the bottom. Figure 14b displays the vertical profile of v during the crest (16.11.2015 hour 02:00), when the assessed longitudinal velocities are all positive values, varying in the range 0.1m/s ÷ 0.25m/s. In this case, the longitudinal current is directed toward the Mar Piccolo basin at all depths. Figure 14c exhibits the vertical profile of the v longitudinal velocities during the passage from tide crest to tide trough (16.11.2015, hours 05:00). It is characterized by negative values in the most superficial layer, meaning the presence of an outflow directed towards the Mar Grande, while positive values are observed at greater depths, starting from z=-5m depth up to the bottom. During the passage of the tide trough (16.11.2015, hours 08:00) shown in Figure 14d, the measured v velocities are negative along the whole depth, with values in the range -0.08m/s ÷ -0.40m/s. This case is thus characterized by an outflow towards the Mar Grande.

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It is worth observing the following. The transit of both tide crest and tide trough rapidly involves the whole water depth, inducing a mass transport, such as a progressive wave (inflow towards the Mar Piccolo for the crest case and outflow from the Mar Piccolo for the trough case). The passage from tide crest to trough (Fig. 14d) highlights that the approaching trough induces a general reduction of the v positive velocities generated during the previous crest transit and causes a flow reversing near the surface, with v values becoming negative. In the passage from trough to crest, the presence of superficial positive v values due to the approaching crest was expected, together with negative values generated by the previous trough transit at greater depths. On the contrary, the vertical profile of v still shows negative values in a thin superficial layer and positive values at greater depths (Fig. 14a). This trend should be interpreted also considering that in the Navigable Channel water temperature and salinity are not uniform along the water column and that a thermohaline gradient occurs. The annual mean salinity distribution investigated in previous researches (Umgiesser, 2007; De Pascalis et al., 2015) showed that freshwater inflows in the Mar Piccolo, from both subaerial watercourses and submarine springs, create an increasing gradient between the Mar Piccolo and the Mar Grande. Moreover, they stated that freshwater stays on the surface layer, while near the bottom salinity is increased of about 1 PSU in most of the basin. Referring to annual averaged temperature trends, De Pascalis et al. (2015) noted that the morphological and bathymetric differences between the sub-systems influence their thermal inertia and create an increasing temperature gradient going from the open sea to the inner part of the basin. Consequently, it seems consistent that during the passage from trough to crest (Fig. 14a) the approaching crest conveys a more saline and cold flux toward the Mar Piccolo, i.e. a dense flux which promptly affects the lower part of the Navigable Channel.

The correlation between tide and currents flowing through the channel was quantitatively investigated in the frequency domain. In fact, also the time series of the longitudinal currents measured at all depths were processed through a spectral analysis, acted by means of the FFT. The amplitude spectrum of the recorded tide level data in the Navigable Channel was therefore compared with each amplitude spectrum of the measured longitudinal current v at all the different water depths. Figure 15 shows these amplitude spectra, obtained for tide (top raw) and for current data at equally spaced depths of 0.5m, starting from z=-1.5m (from second to ninth row).

The two the peaks of amplitude in the spectrum of tide levels, at frequencies corresponding to 12h and 24h respectively already noted in Figure 3a, are also present in the amplitude spectra of the current signals, at all the investigated depths (Figure 15). In addition, the current amplitudes on both these frequencies slightly decrease from the surface toward the bottom, revealing that the tide effect is stronger in the most superficial layers. Finally, it can be stated that the current flow in the Navigable Channel could also be affected by wind or thermohaline actions, but is undoubtedly dominated by the semidiurnal tide.

It is worth noting that if changes in the configuration do not occur, it could be possible to extrapolate patterns of flux behaviour useful for prediction. The observed correlation between tides and currents in the channel suggests a well-defined and thus reproducible modification of the vertical flow due to the passage of the tide. On the contrary, if modifications in the configuration occur, extrapolating patterns is possible only if such changes have been captured in the measurement records. In this second case, numerical simulations could conveniently integrate foreseen hydrodynamic scenarios.

4 Discussion and concluding remarks

Understanding water circulation in coastal bays and exchanges with open sea is a prerequisite for sustainable management of these systems. Several studies have addressed the exchange and transport processes between lagoons and open sea, but

most detailed process models do not necessarily answer questions at the time and space scales of interest for coastal communities. At the same time, the increasing availability of field measurements due to monitoring programs seems to guarantee a more complete investigation of the mechanisms driving coastal processes.

Once noted the huge and increasing amount of measured data coming from marine sensors and instrumentations, in the present paper we focused on the necessity to transform these row data into information according to users' catchment. Rather than providing tools for predictions, we outlined a simple framework applicable to any coastal site which allows to deduce recurring trends and typical hydrodynamic behaviours starting from data sets. The requirements of this strategy are i) the high quality of the available data, ii) the application of well-established and classical procedures with low computational cost. While the first request acts as a limitation in the framework applicability, the second one provides it added value, meaning that the techniques used to manipulate data and extract information can be feasibly and successfully adopted.

To show how this framework can be implemented, its components were sequentially applied to some field measurements available within the study case of the Mar Piccolo semi-enclosed basin. The high quality of these data was guaranteed since field wave, tide and 3D-current measurements were acquired continuously, at the same location, at the same time, with hourly frequency and for a whole autumn-winter season (three months).

Following the methods based on residual flow determination (Janzen and Wong, 1998; Guyondet and Koutitonsky, 2008) and on tidal asymmetry (Aubrey and Speer, 1985; Jewell et al., 2012; Di Lorenzo, 1988) the data processing was scheduled both in time and frequency domain, with successive time-averaging and phase-averaging techniques as well as with FFT algorithm. In this simple way, we responded to the necessity of: filtering out spurious signals; analyse the current spreading from superficial to bottom layers, along the tidal period; searching for possible correlations between tide levels and water currents measured at different depths; detecting on the tidal asymmetry and on flood or ebb dominance. Further, this sequence of operations on data inferred the identification of some state indicators, which are quantitative parameters providing more insights on specific behaviours of the coastal basin. At the same time, they also permitted information on the interactions among waves, tides and currents, so that the key mechanisms governing the fluxes flowing through the basin in the reference period were captured.

Specifically, the following indicators were derived along with the steps of the framework: i) the net flow crossing the channel, ii) the time delay of current peaks between upper and bottom layers, iii) the ratio of peak ebb and peak flood currents, iv) the tidal asymmetry factor. The principal findings due to the estimate of these indicators can be summed up in the following way. The values assumed by the net flow indicator reveals that a double circulation occurred in the connecting channel, with inflowing flux in the deeper layers and outflowing flux in the most superficial ones, confirming both numerical modelling (De Pascalis et al., 2015) and previous field data analysis (Armenio et al., 2016; De Serio and Mossa, 2016a). The second indicator shows that the transit of both tide crest and tide trough rapidly involved the whole water depth, inducing a mass transport such as a progressive wave, which vertically affected the current with a time delay equal to two-three hours. The third and fourth indicators both confirm a flood dominant condition in the basin.

It is worth noting that the above written indicators are obviously linked to the investigated site and to the features of the assessed signals. In any way, due to the undeniably replicability of the framework which is not site-specific, we can state that any basin system can be characterized by indicators deduced following this scheme, since they represent a link between forcing data (tide) and response data (currents). In this sense, we could simply but adequately describe the state and the evolutionary trend of tide-current interaction in any investigated basin, where cyclic behaviors are expected to recur. This way to convert high-quality field measurements in information for stakeholders is therefore simple, immediate and flexible, requiring low computational resources and being independent of any process-based modelling package. In

this framework, the importance and the role of high quality field measurements cannot be understated, being the quantity, quality and duration of observations hot factors which constitute an extremely valuable resource. Finally, we could even attempt a forecasting of the response data over short timescales, i.e. time spans that are considerably shorter than the length of the investigated data time series. Preferably, considering this approach as a starting point, the successive step to provide forecasts could be drawing on it to further analyse coastal physical processes also in conjunction with modelling methodologies.

Acknowledgements

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Tidal constituents	Q1	O1	K1	J1	N2	M2	L2	S2	M3	M4	S4	M6	M8
Phase (θ) (degrees)	348.4	21.8	152.0	258.4	152.0	162.9	270.0	347.8	243.6	180.9	301.3	203.2	264.7
SNR	0.064	0.7	4.1	0.45	2.8	17	3.4	2.3	2.1	1.9	0.85	0.64	0.06

Table 1: Phase and signal-to-noise ratio (SNR) of tidal constituent.

a)

b)

Figure 1: Map of the study area of Mar Piccolo in the south of Italy, b) enlargement on the position of station A and station B in the Navigable Channel. Source Google Earth.

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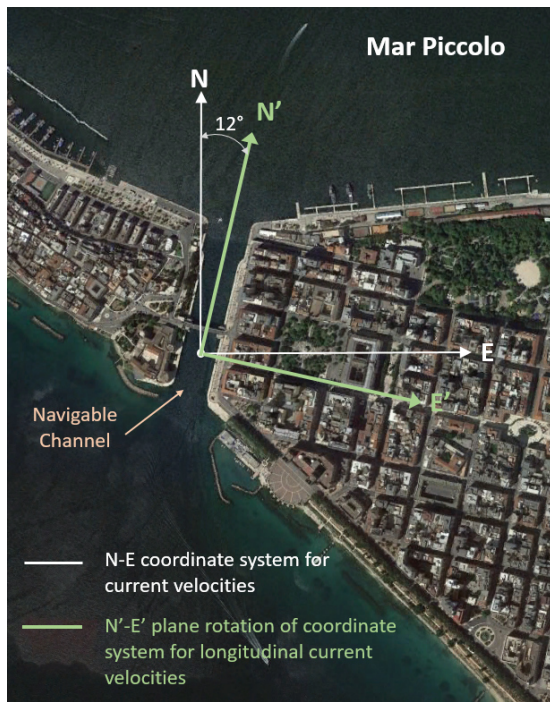
Figure 2: Initial coordinate system adopted for current velocities (white) and plane rotation of the coordinate system for longitudinal current velocities (green)

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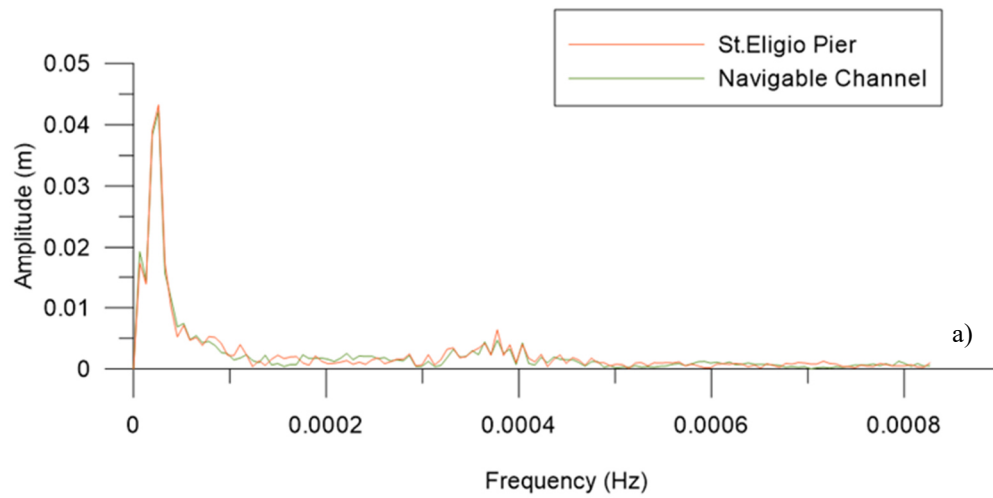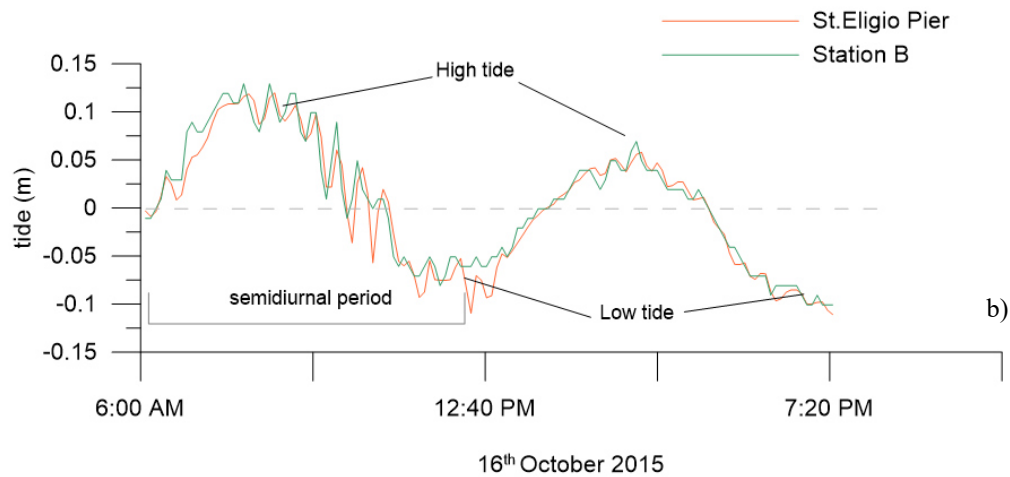
Figure 3: Comparison between a) the amplitude spectra of tidal data recorded by Station B and Station St. Eligio; b) the tidal signals measured at Station B and Station St. Eligio during the extreme meteorological event, on 16.10.2015.

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c)
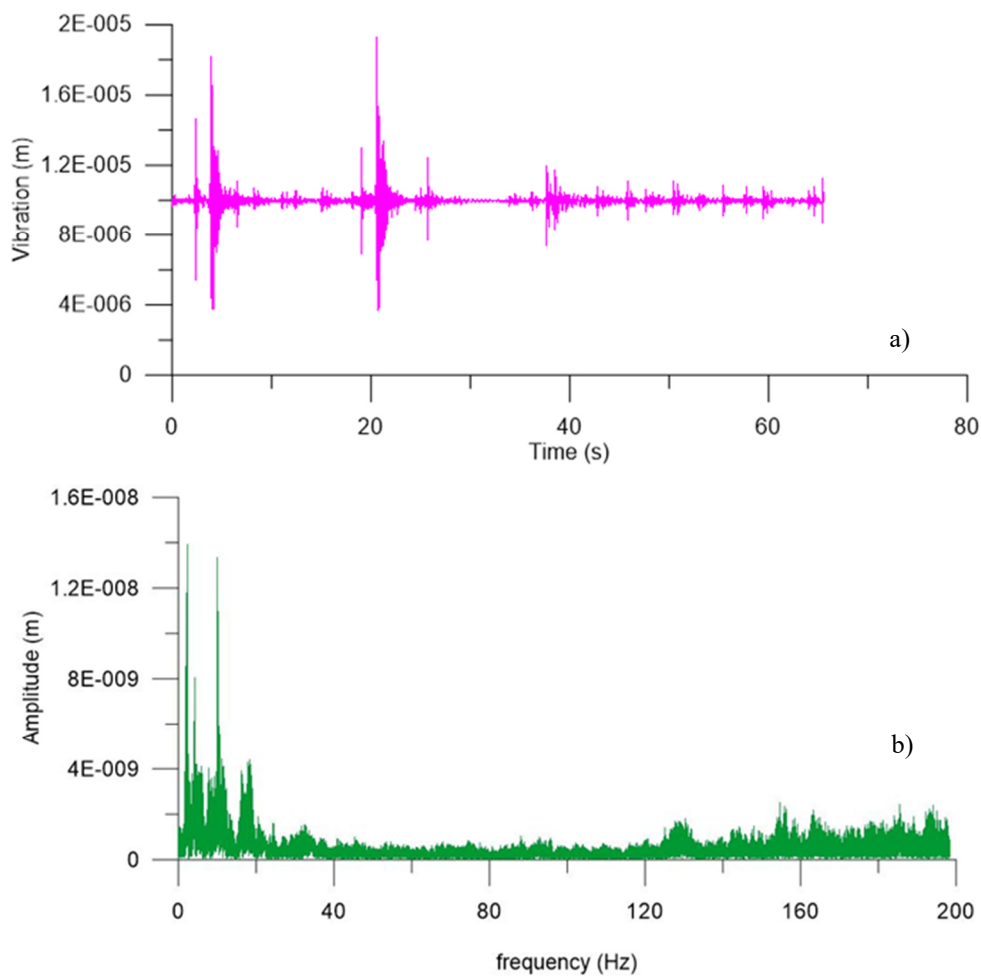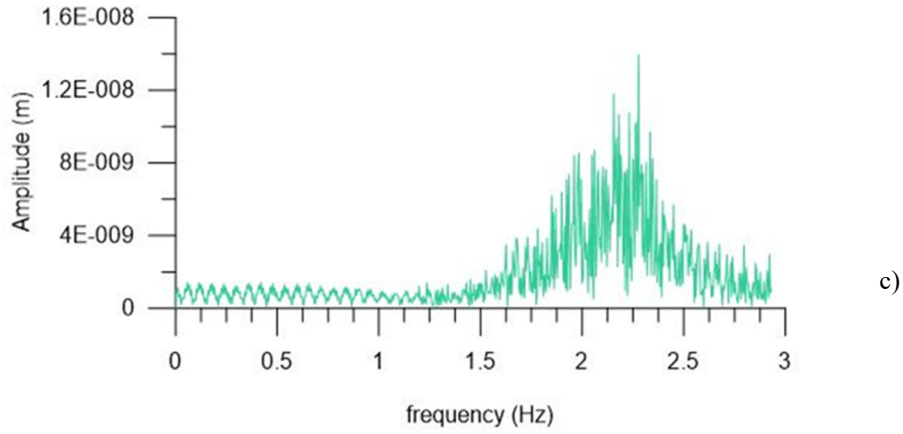
Figure 4: a) Time series of bridge vibrations; b) Amplitude spectrum of bridge vibration; c) Enlargement of the amplitude spectrum in the frequency range 0 ÷ 3.0 Hz.

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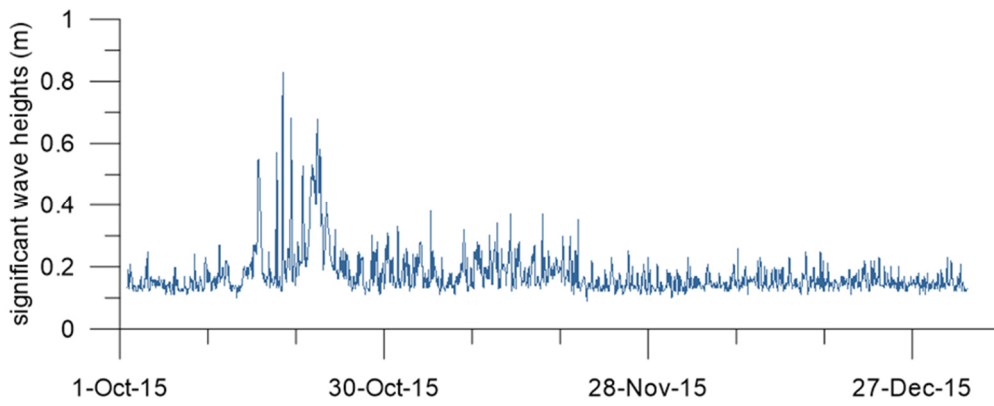
Figure 5: Time series of the significant wave heights *Hs* for the investigated period.
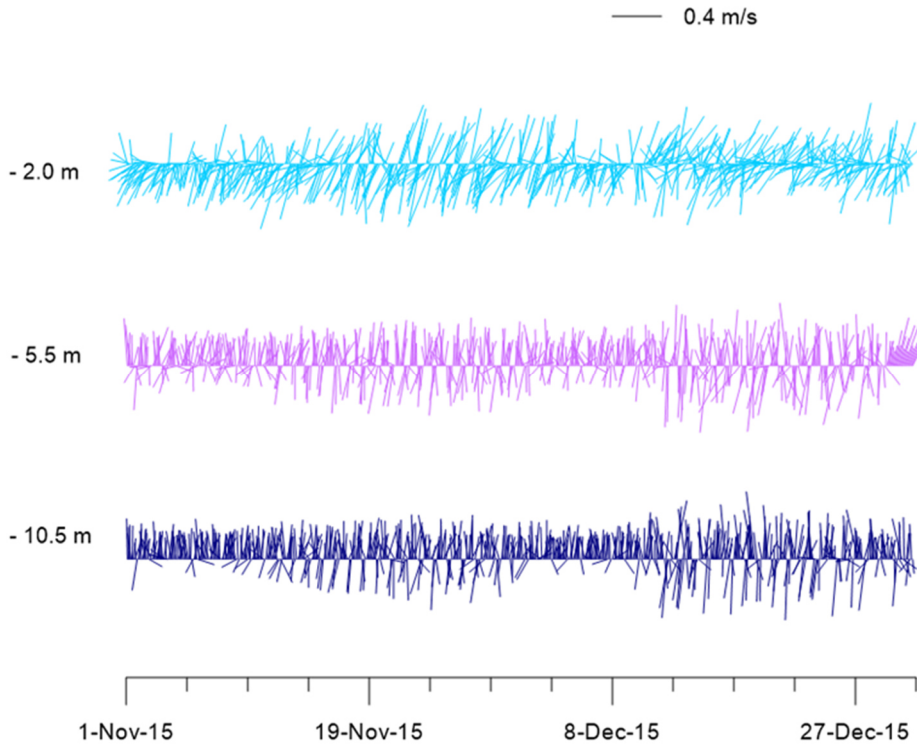
Figure 6: Stick plot of the current vectors at depths z=-2.0 m, z=-5.5 m and z=-0.5m from surface.
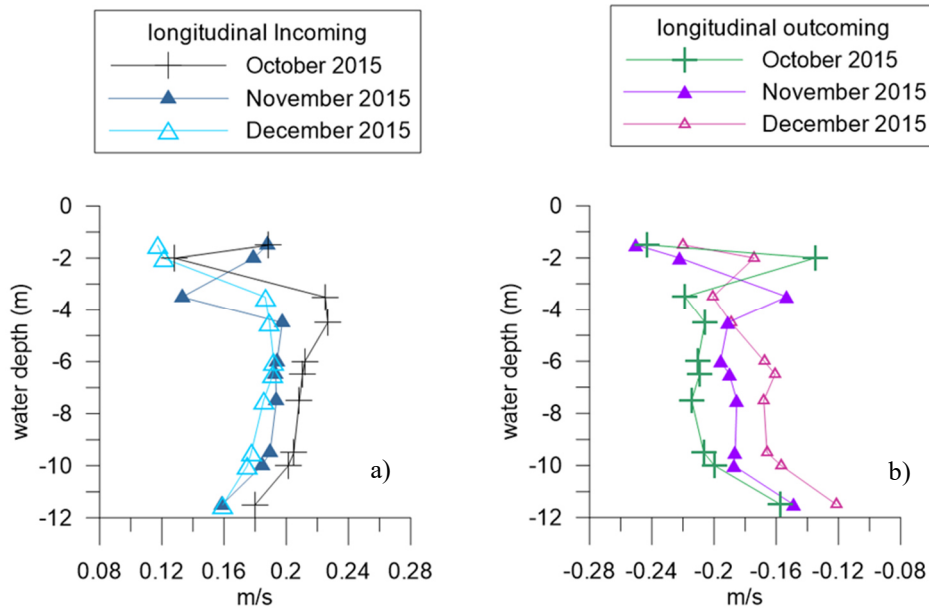
Figure 7: Monthly-averaged values of the longitudinal components of a) the incoming flow and b) the outcoming flow.

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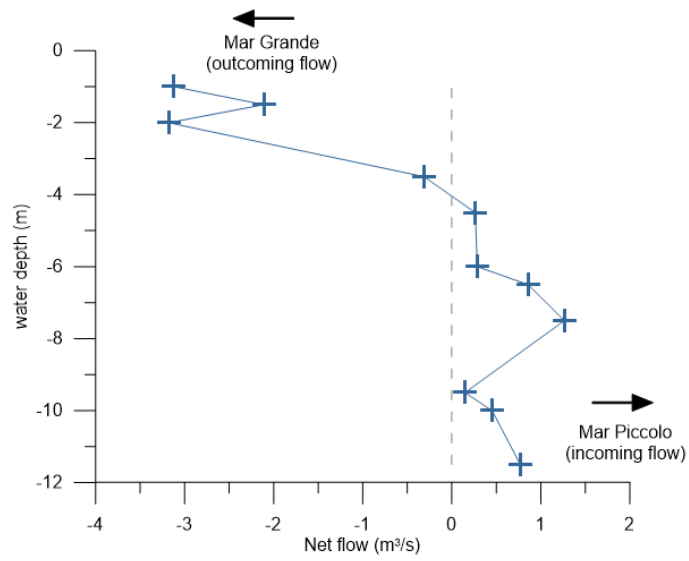
Figure 8: Net flow across the Navigable Channel in the reference period.
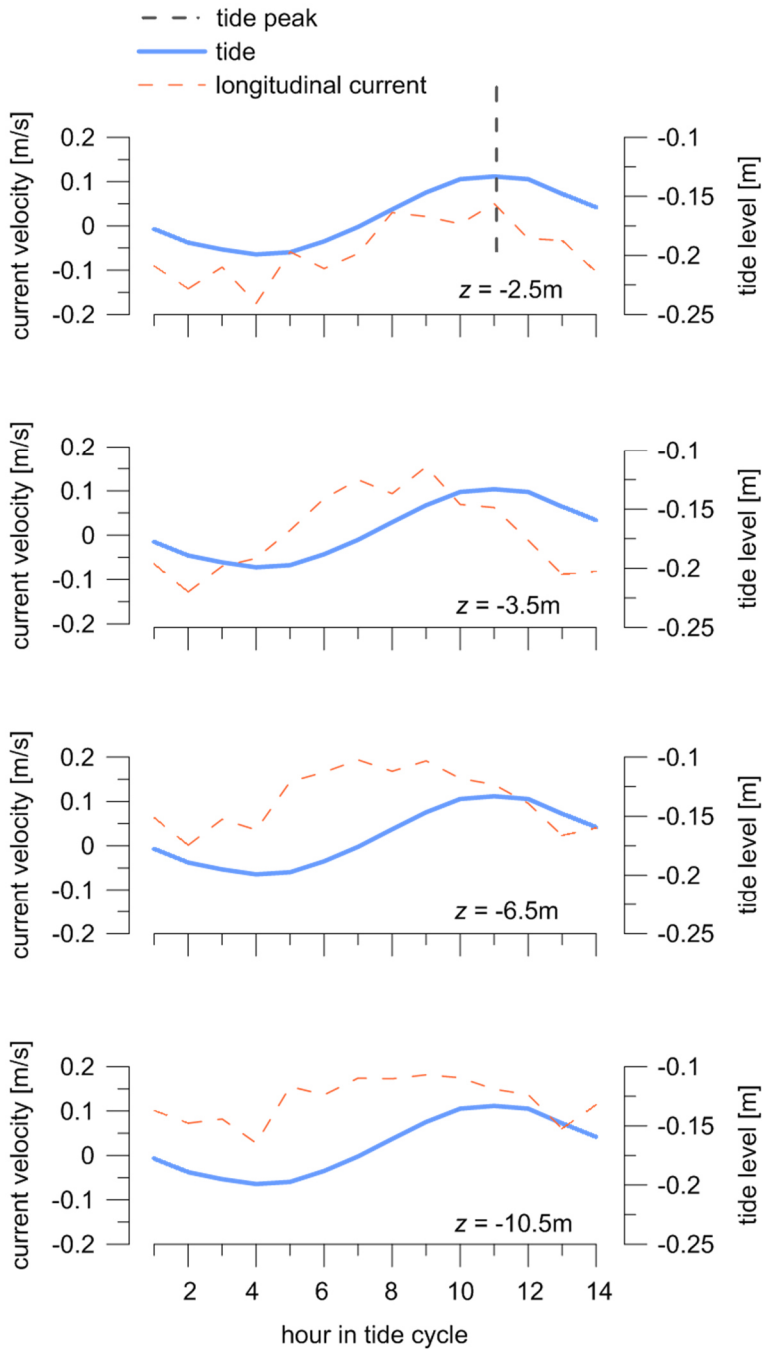
Figure 9: Phase-averaged tidal elevations (blue line) and longitudinal current-velocities (dotted orange line) at some selected depths z.

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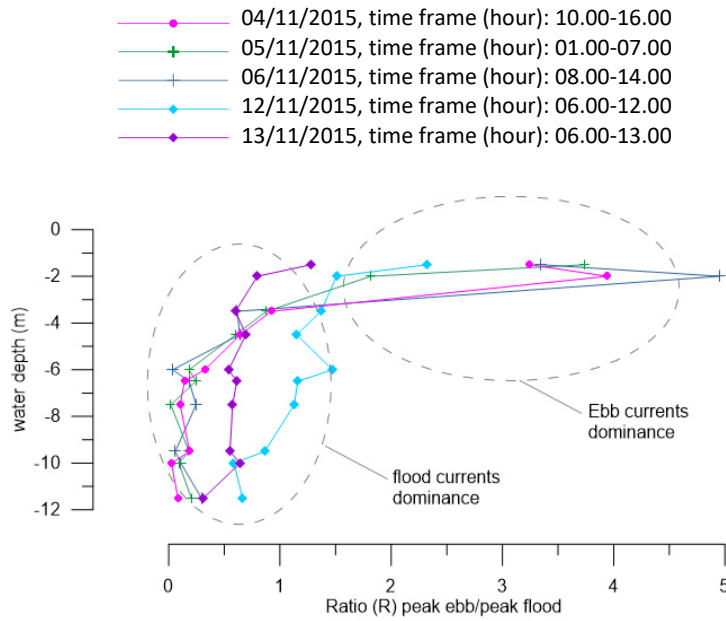
Figure 10: Ratio *R* for different water depth for five selected time frames.
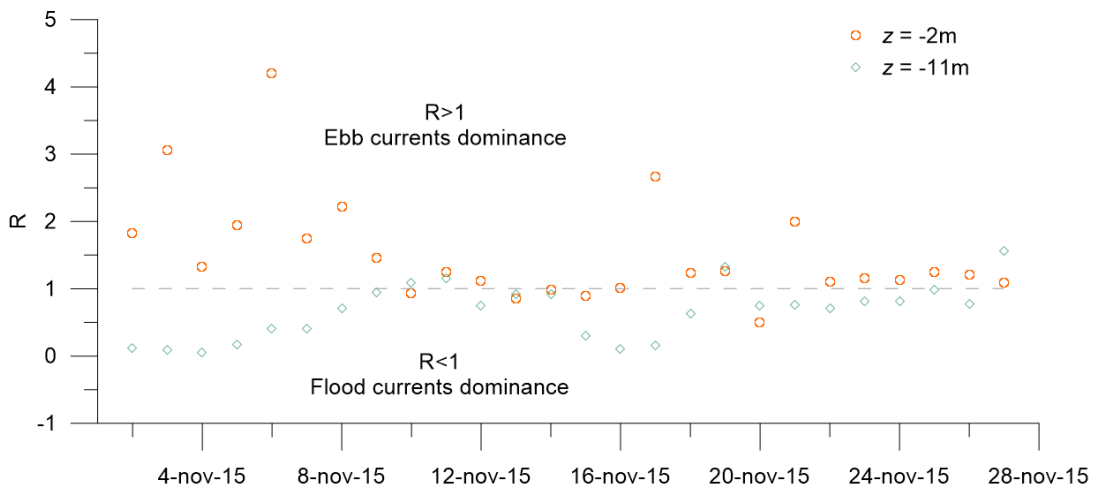
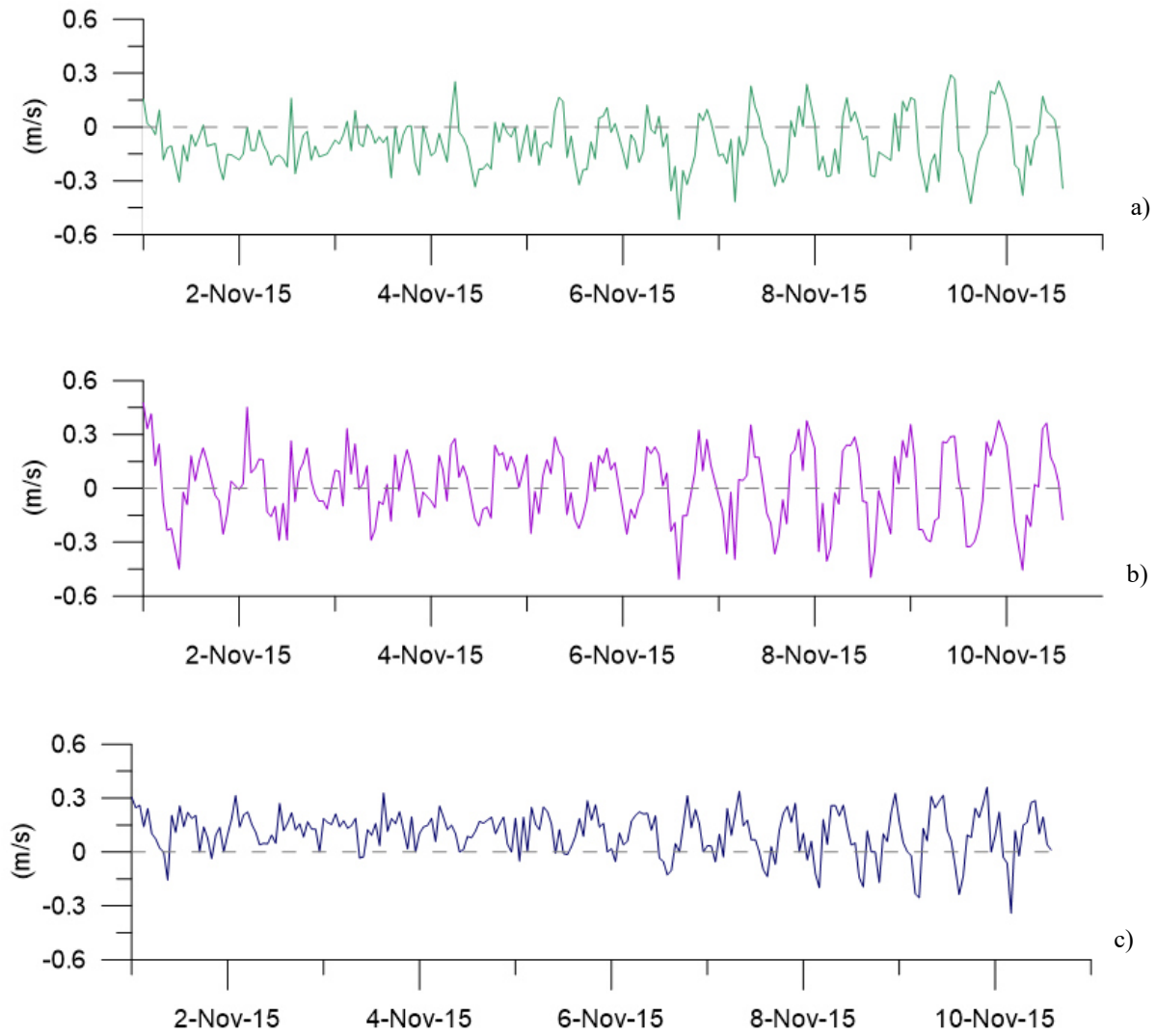**Figure 11: Monthly variability of the ratio R for November 2015, near the surface and near the bottom.**

Figure 12: Duration of floods and ebbs at a) *z*=-2.0 m, b) *z*=-6.0 m and c) *z*=-10.5m. Time window from 01.11.205 hour 00:00 a.m. to 10.11.2015 hour 09:00 p.m.
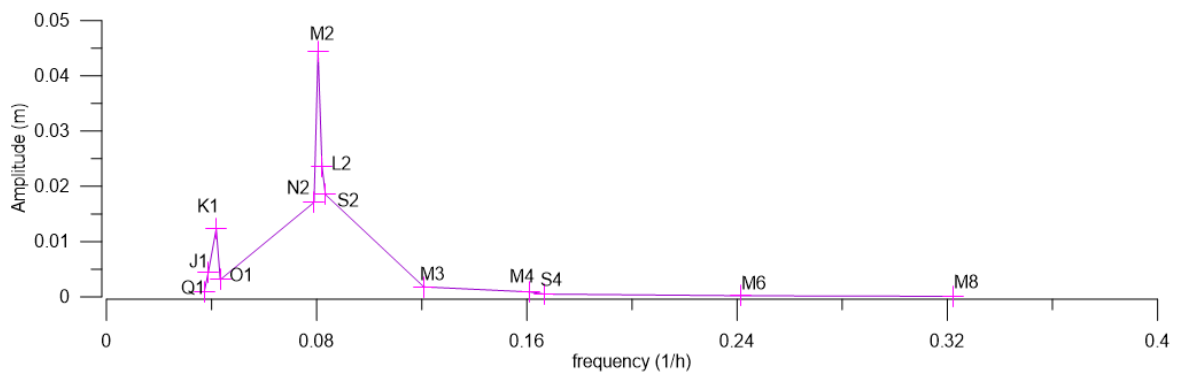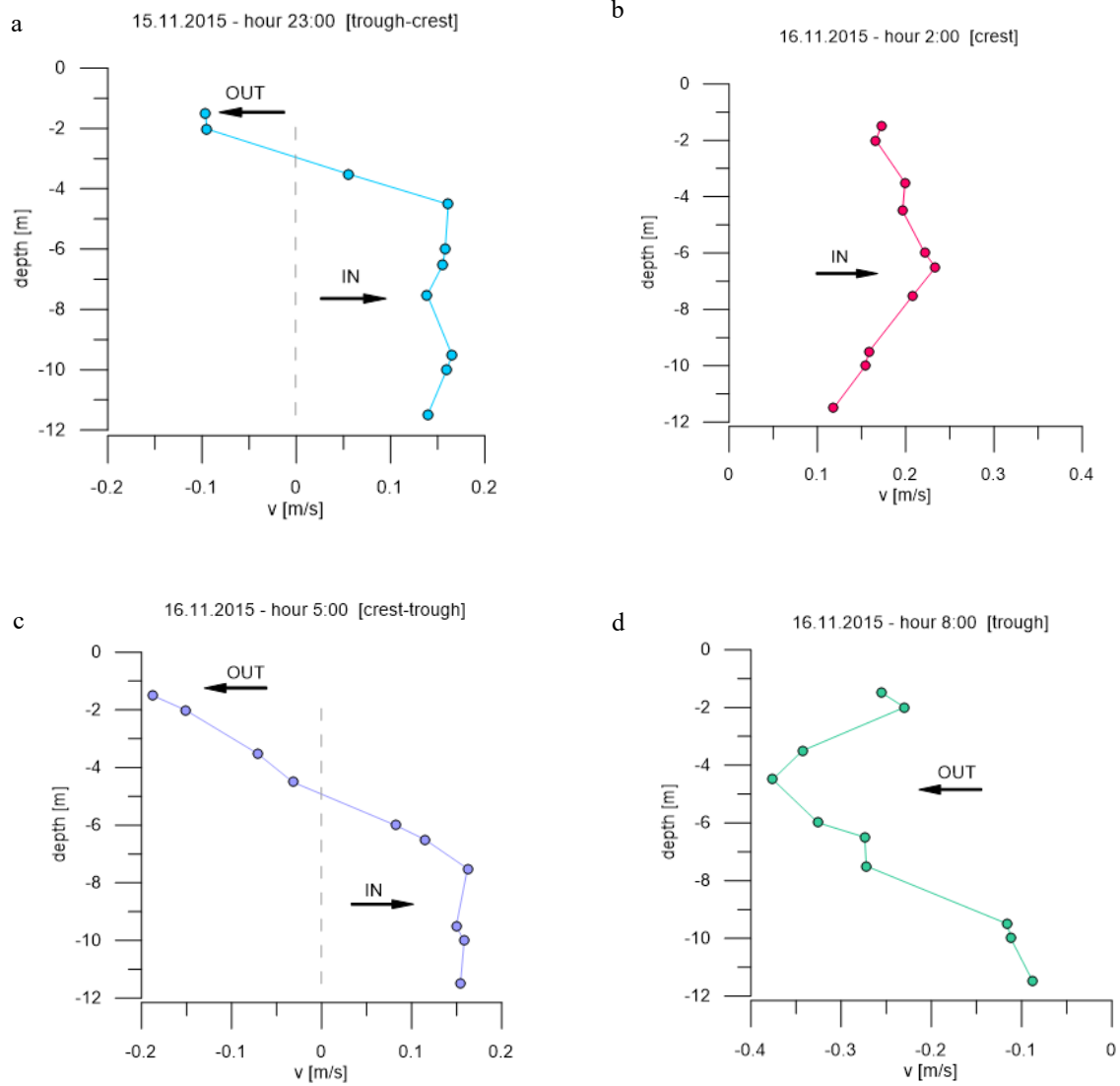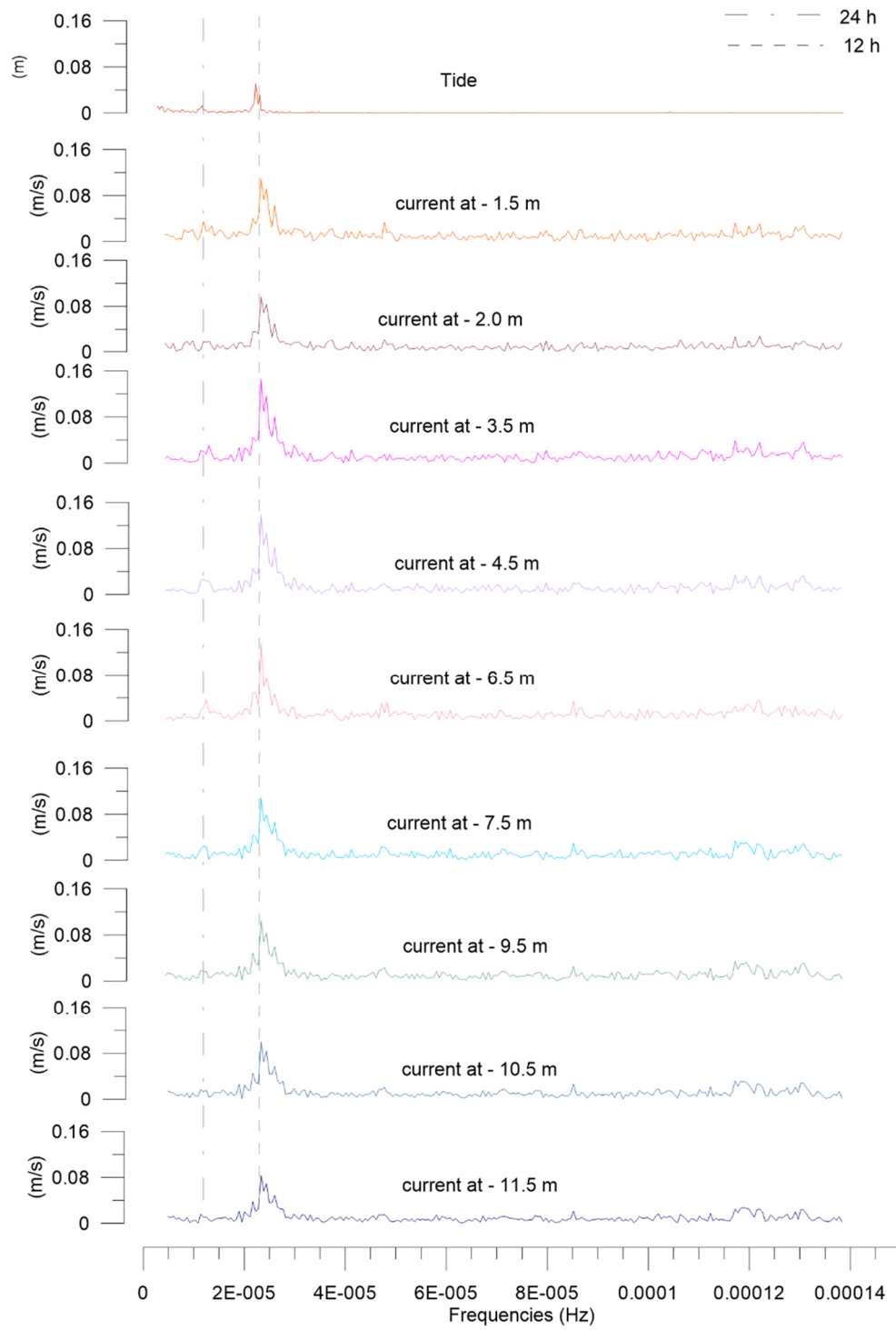
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Figure 13. Summary of the harmonic analysis results for tides recorded at Station B.

5   **Figure 14: Vertical profiles of the longitudinal current velocity v at four different instant times, along a tidal cycle.**

Figure 15: Amplitude spectrum of tide data (m) at Station B and of the longitudinal current velocity at Station A (m/s) for different water depths from surface.

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