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Multiyear high-frequency physical and environmental observations at the Guadiana Estuary

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Abstract

High-frequency data collected continuously over a multiyear time frame are required for investigating the various agents that drive ecological and hydrodynamic processes in estuaries. Here, we present water quality and current in-situ observations from a fixed monitoring station operating from 2008 to 2014 in the lower Guadiana Estuary, southern Portugal (37°11.30′ N, 7°24.67′ W). The data were recorded by: a multi-parametric probe providing hourly records of temperature, chlorophyll, dissolved oxygen, turbidity, and pH at a water depth of ∼ 1 m; and, a bottom-mounted acoustic Doppler current profiler measuring the pressure, near-bottom temperature, and flow velocity through the water column every 15 min. The time-series, in particular the probe one, present substantial data gaps arising from equipment failure and maintenance, which are ineluctable with this type of observations in harsh environments. However, prolonged (months-long) periods of observations during contrasted external forcing conditions are available. The raw data are reported together with quality flags indicating the status (valid/non-valid) of each record. Hourly river discharge data from two hydrographic stations located near the estuary head are also provided to support data analysis and interpretation. The dataset is publicly available at PANGAEA (doi:10.1594/PANGAEA.845750) in machine-readable format.

1 Introduction

Estuaries are one of the most productive types of ecosystems on Earth and are of considerable value to both humans and wildlife. Despite extensive research efforts during past decades, the preservation of these systems demands a greater knowledge and understanding of the complex physical and biological mechanisms that control their health (Kennish, 2002; Zalewski, 2013). In particular, multiyear in-situ observations made at high (minutes to hours) frequencies are desirable for investigating the various agents that drive their ecology and hydrodynamics. Although increasingly implemented

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in highly developed countries, such monitoring programmes are not yet carried out worldwide in estuaries (Baptista, 2008; Dang, 2010; Garel et al., 2009a).

The SIMPATICO (integrated System for In-situ Multi-PArametric moniToring In COastal areas) station has been operating since March 2008 in the lower Guadiana Estuary for the in-situ continuous monitoring of current and water quality (Garel and Ferreira, 2011a; Garel et al., 2009a). This estuary, at the southern border between Spain and Portugal, is 80 km-long, narrow (700 m at max) and generally less than 10 m-deep (referred to the mean water level). It is oriented north–south and connects directly the Guadiana River (810 km-long, having the 4th drainage area of the Iberian Peninsula) to the Gulf of Cadiz (Fig. 1). Numerous studies have established its physical (Boski et al., 2002; Fortunato et al., 2002; Garel and Ferreira, 2013; Garel et al., 2009b, 2014; Lobo et al., 2004; Morales et al., 2006; Sampath et al., 2015) and ecological (Barbosa et al., 2010; Camacho et al., 2015; Domingues et al., 2011, 2012) settings. The primary motivation for the deployment of the SIMPATICO station at this location was to perform a multi-parameter and multi-scale real-time environmental monitoring in a context of growing anthropogenic pressure. The latter is related mostly to tourism development, land use changes and strong flow regulation owing to increasing freshwater demand (Dias et al., 2004; Garel et al., 2009a; Guimarães et al., 2012). In particular, more than 100 dams were built since the 50s' in the river basin, including the controversial Alqueva dam on the Guadiana River, closed in February 2002 to form the largest reservoir in Western Europe at only 80 km from the estuary head.

The SIMPATICO monitoring station includes a multi-parametric probe providing hourly observations near the surface and a bottom-mounted Acoustic Doppler current Profiler (ADP) operating at 15 min intervals. The system is currently (May 2015) out of water for maintenance but is planned to be redeployed at the same location. This contribution presents the data collected by this instrumentation between 2008 and 2014, together with the concurrent freshwater discharge into the estuary (Table 1). First, a description of the SIMPATICO system is given (Sect. 2). Then, the techniques used for data validation are detailed (Sect. 3). In Sect. 4, an overview of the data is

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provided. As a conclusion (Sect. 5), some of the key eco-hydrodynamic aspects that can be addressed by the dataset are outlined.

2 The SIMPATICO monitoring station

The SIMPATICO system is located at the lower Guadiana Estuary, near the mouth, ∼ 3 km from the tips of a pair of jetties that have stabilised the inlet and ∼ 100 m from the Portuguese shore (37°11.30′ N, 7°24.67′ W) in front of Vila Real de Santo Antonio (red star in Fig. 1). This location is close to the nearest part of the estuarine channel (see Garel and Ferreira, 2013). The station is constituted with a foam-hull floating platform (YSY EMM 550; YSI, 2007) measuring 90 cm in diameter, anchored to the seabed with chains and concrete blocks (Fig. 1). Inside the buoy, a water-tight electronic compartment houses a datalogger (CR1000; Campbell Scientific, 2006) as well as batteries that provide power to the system and which are recharged by three solar panels located on top of the buoy. The logger is equipped with a modem for the automatic downloading of raw data to a remote server through Global System for Mobile Communications (GSM).

The multi-parameter probe (YSI 6600 V2-4; YSI, 2006) is inserted through the surface buoy, measuring (hourly) water quality parameters at 1 m water depth. It is equipped with three optical sensors to measure turbidity (NTU), both saturated (%) and dissolved (mg L^{-1}) oxygen levels, and chlorophyll concentration (µg L^{-1}, via fluorescence), as well as three other non-optical sensors to measure conductivity (µS cm^{-1}), temperature (°C), and pH (Table 1). Water conductivity is derived from the decrease in voltage recorded within a cell fitted with four nickel electrodes. Temperature (ITS-90 scale) is converted from resistance variations measured with a precision thermistor of sintered metal oxide. Salinity (PSU) is determined internally from the conductivity and temperature readings according to standard methods (Clesceri et al., 1989). The pH probe determines hydrogen ion concentration using a combination electrode consisting of a proton-selective reservoir (filled with a pH 7 buffer) and a Ag/AgCl reference

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electrode. A fluorometer is used to estimate the concentration of chlorophyll in vivo based on the ability of chlorophyll to fluoresce (however, the distinction between the different forms of chlorophyll is usually not possible). Dissolved oxygen is obtained by measuring the lifetime luminescence of a dye exposed to blue light. Turbidity is determined by shining a light beam into the sample solution and then measuring the amount of light scattered off suspended particles. The optical sensors are fitted with wipers for cleaning the optical face before measurement. All sensors (except the temperature sensor) require periodic calibration using buffer solutions (for details, see Sect. 3). For chlorophyll, because of the lack of appropriate buffer, a zero calibration designed to evaluate the sensor drift is performed using distilled water; as such, the fluorescence sensor provides semi-quantitative chlorophyll measurements that are useful for detecting changes over time (rather than accurately measuring concentration levels). For the other sensors, data accuracies provided by the manufacturers are ±0.15 °C for temperature, ±0.5 % for conductivity, ±1 % for salinity, ±0.2 for pH, ±2 % for dissolved oxygen, and ±5 % for turbidity.

The 750 kHz ADP (Sontek Argonaut XR; Sontek/YSY, 2001) is bottom mounted on a structure (spider) fixed to a concrete block, about 10 m north and 5 m west of the buoy, in 9 m water depth (referred to mean sea level; Fig. 1). The acoustic signal is emitted at 1 Hz from three beams slanted 25° off the vertical and equally spaced at 120°. The ADP includes a high-resolution pressure sensor as well as compass/tilt and temperature sensors. The distance between the base of the concrete block and the top of the ADP is ~ 1 m. The three velocity components (east, north, and vertical) of the flow are measured in 10 cells each 0.8 m thick (multi-cell data, hereafter) along the water column (Table 1). In addition, depth-integrated velocities are measured in a cell (main-cell data, hereafter) whose vertical extent is adjusted automatically near the surface based on the pressure records. Both the main-cell and multi-cell measurements start at 0.8 m above the instrument, and therefore 1.8 m above the bottom; however this distance varied through time owing to changes in bed elevation, and in particular to the burying and tilting of the mooring structure with the episodic passage of sand

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dunes (Garel and Ferreira, 2011a; Lobo et al., 2004; Morales et al., 2006). ADP ensembles are averages of 5 to 15 min measurement periods (depending on the time series considered), collected at 15 min intervals.

3 Data validation

3.1 Probe data

Probe data were validated based on the analysis of unexpected deviations from ranged values taking into consideration the dates of sensor maintenance (i.e., cleaning and calibration). Technical problems with the probe sensors caused non-realistic measurements that were easily identified in the time series. Apart from technical issues, the main concern in the continuous acquisition of (valid) data was biofouling (Garel and Ferreira, 2011a). The development of biofouling on the optical sensors produces a characteristic spiky signal tending towards saturation. Likewise, biofouling within the conductivity cell induces a typical progressive decrease in both the maximum and minimum readings. Other parameters recorded by the probe and external factors (such as river discharge or tidal phase and amplitude) were also taken into account to help distinguishing between natural and biofouling-induced variations. Antifouling paint was used at the beginning of the deployment, but this generated poor results with respect to the length of valid measurements (often less than 2 weeks). The use of a copper-based anti-fouling kit from February 2009 onwards provided protection over a longer period (3 to 4 weeks).

Probe maintenance was performed depending on boat and staff availability and on weather conditions. Maintenance consisted in meticulous cleaning of the probe and in sensor calibration (the dates of these operations are included in the presented dataset). Following the manufacturer recommendations, a 1- or 2-point calibration (depending of the sensor) was performed (every ~ 3 months, in general), using buffer solutions that are near the range of variation of the measured parameters: for conductivity, 1-point cal-

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ibration with a 50 mS cm^{-1} solution; for pH, 2-point calibration with 7 and 10 solutions; for turbidity, 2-point calibration with 0 and 12.7 NTU solutions; for dissolved oxygen, 1-point calibration in water saturated air environment; and, for chlorphyll, 1-point calibration with clorophyll-free solution. The turbidity- and chlorophyll-free solutions were obtained from distilled water filtered at 0.22 µ. Data spikes related to maintenance operations were invalidated. Small shifts in intensity are observed in some cases in the pre- and post-calibration time-series (particularly for salinity) because of sensor calibration inaccuracy (the quality of each calibration depends on the choice of buffers and procedures, as well as on operator skill, with all these aspects affecting the reliability of the measurements). The data presenting such (small) discordances were regarded as valid. Similarly, inaccurate calibration of the turbidity sensor may produce negative values (when the concentration of suspended material is very low), and in these instances the values were set to zero.

3.2 ADP data

Quality control of the ADP data was applied to each individual multi-cell and main-cell (depth-integrated) velocities. Threshold values were selected based on manufacturer recommendations, careful data inspection, and site knowledge (Table 2). A few temperature and pressure records were obviously erroneous (e.g., a temperature of $> 50\,^{\circ}$C) and were removed from the raw time series. In contrast, all (raw) velocity records were included in the dataset and flagged as valid or non-valid based on the results of the quality control.

For the main-cell data, the quality control includes a check of the instrument tilting, of the beams' signal-to-noise ratio (SNR), of the standard deviation of velocities, and of the beams' signal strength. The SNR was computed as (Sontek/YSY, 2001):

$$\text{SNR} = 0.43(\text{signal strength} \times \text{signal noise}) \quad (1)$$

We also verified that the upper limit of the sampling volume used to compute the depth-integrated velocities is close (within 1 cell size) to that predicted (CP) based on the

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pressure (P) and its standard deviation (SD_P), using (Sontek/YSY, 2001):

$$CP = 0.9(P - 2 \times SD_P) \tag{2}$$

In cases where the main-cell data of a given ensemble did not pass the quality check, all the corresponding multi-cell data were also flagged as non-valid. In addition, multi-cell data quality control was performed based on the difference in SNR between the three beams and on the velocity standard deviations (Table 2). Velocity records in the cell located near the surface boundary (and in the cells above, which are in the air) were also discarded based on pressure records (using Eq. 2) and on signal amplitude (typically, the mean amplitude decreases as the signal propagates upward, but increases near the boundary owing to strong reflection that compromises the accuracy of the readings).

4 Datasets overview and access

The dataset (March 2008–April 2014) is provided, for each year, in the form of machine-readable (tab-delimitated) text files with extensive information (in header) about the site, instrument, hardware, setup, and units. Both raw data and flags indicating the quality of each record (valid or non-valid; see Sect. 3) are reported, allowing a user to reprocess the data.

The multi-parametric probe raw data include temperature (°C), pH, dissolved oxygen ($mg\,L^{-1}$), turbidity (NTU), salinity (PSU) and chlorophyll ($\mu g\,L^{-1}$). Invalid data are denoted with a slash before the reading (e.g., \xxx where xxx is a raw record). To facilitate data quality assessment by other users, the dates of probe maintenance (inspection and cleaning) and of sensor calibration are also included in the dataset (see also Fig. 2a). The station was pulled out of water in February 2010 for complete maintenance after a major system failure related to large floods (Fig. 2a). This event produced a large gap in the probe time series from 15 February 2010 to 26 January 2012.

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Episodic probe faults produced additional shorter data gaps of maximum 1 month duration, except on 26 November 2008–2009 February 2009 (74 days) and on 07 May–22 September 2009 (138 days; see Fig. 2). Overall, substantial data gaps occur within the 2008–2010 period, while the period 2012–2013 is more complete (Fig. 2a).

The ADP time series report the parameters displayed in Table 1. Sensor data include pressure (dbar), pitch and roll (°) and temperature (°C). Diagnostic parameters – helpful in assessing data quality – are beam noise, amplitude and strength, reported in counts (an internal logarithmic unit representing 0.43 dB). Velocity data ($m\,s^{-1}$) include the main-cell and multi-cell velocities and their quality status (1: validated; 0: non-validated). Standard deviations of the pressure, pitch, roll and both main-cell and multi-cell velocities are also reported. The magnetic declination (changing at a rate of 0°7′ E per year in the area) was corrected according to the mean declination of each of the three periods. The pulse length was changed from 2 to 1 m in May 2009, resulting in an improvement of the performance of the ADP near the surface boundary (fewer cells were contaminated by signal reflection and therefore invalidated), but with no effect on the main-cell velocities. The previously mentioned data gap related to system failure stretches from 04 January 2010 to 07 December 2011. Defective connectors caused another large data gap between 12 December 2012 and 02 March 2013. Overall, three long time-series of continuous data (except few minor gaps) are available, ranging from (1) 19 March 2008 to 04 January 2010, (2) 07 December 2011 to 12 December 2012, and (3) 02 March 2013 to 08 April 2014 (Fig. 2b).

To assist with the interpretation of the datasets and to enhance their potential use, hourly river discharge data ($m^3\,s^{-1}$) were compiled from March 2008 to April 2014 (Fig. 3). Water levels were obtained from two automatic hydrographic stations of the Portuguese Water Institute (INAG; presently APA, Portuguese Environment Agency): Pulo do Lobo and Ponte Quintos, located about 20 and 40 km from the estuary head, respectively, and catching the runoff from 90 % of the Guadiana river basin. The river discharge was converted from water level records using calibration discharge curves specific to each station (see http://snirh.pt). The two datasets are complementary:

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the time series from Pulo do Lobo station is patchy, in particular from 2010 onwards, whereas that from Ponte Quintos is more continuous, although with frequent hours-long data gaps. The stations have not been maintained since March 2010, and therefore the quality of the data is not guaranteed from that date. However, consistency between the two time-series gives confidence in the discharge values. Also, the expected discharge patterns in response to flow regulation are observed and are associated with congruent variations in salinity at the SIMPATICO station (probe data). The predominantly low discharge (around $50\,m^3\,s^{-1}$) in 2011–2012 (*ii* in Figs. 2 and 3) corresponds to the minimum (so-called environmental) flow released from the Alqueva dam for sustaining ecosystem health (Dyson et al., 2003). The discharge reaches near-zero when water storage within the reservoir is prioritised, such as before 2010 and during the drought year of 2012 (*i* in Figs. 2 and 3), producing a marked reduction in the minimum values of salinity (Fig. 2). Episodically, water released from the dam produces short periods of moderate to high river discharge, ranging from 400 to $2500\,m^3\,s^{-1}$ that are associated with moderate to large decreases in salinity (*iii* in Figs. 2 and 3).

The dataset presented here is deposited at PANGAEA in machine readable format (tab-delimitated text files). Each type of data (water quality data, probe maintenance dates, current measurements and river discharge) is referred to with explicit file names. The dataset is available publicly (Creative Commons Attribution 3.0 Unported License) at doi:10.1594/PANGAEA.845750.

5 Conclusions

This contribution presents flagged data from a current-meter and a multi-parametric probe operating between 2008 and 2014 at the lower Guadiana Estuary, together with the concurrent freshwater discharge. Although the time series contains various extended periods with gaps (in particular the probe data in 2008–2010), scientific interest in these data lies in the availability of physical and environmental observations of the estuarine conditions at high frequencies for both prolonged periods (in partic-

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ular in 2012–2013) and contrasted external forcing conditions. As such, the dataset provides the research community with an important data source for the study of hydrodynamic and eco-hydrodynamic processes acting in estuaries at subtidal to seasonal time scales. It also contributes to the development of comparative science in international context, such as the one promoted by "Our Global Estuary" initiative (http://wordpress.fau.edu/oge/). Furthermore, ith strong flow regulation at the Guadiana Estuary, potential data usages include studies of the effects of large dams, towards the development of best flow regulation practices.

One example of application of the presented dataset is to support the development of numerical (hydrodynamic and ecological) models through the evaluation of simulation results near the estuary mouth against the presented data. In particular, coupled hydro-ecological models are increasingly used in estuaries (Robson, 2014) but their performances are rarely evaluated against high frequency datasets of several months long. Such assessment using the present dataset should be conducted for validation purposes only as model calibration should be based on observations at various locations along the system. On request, the authors can provide measurements performed episodically at other locations in the estuary together with other complementary data useful for model implementation such as bathymetric and surface sediment maps.

The presented dataset also allows the study of complex interacting hydrodynamic processes, especially when those require long term observations at high frequency in order to be specified. For example, previous studies have shown that the vertical structure of the barotropic boundary layer can be distinguished from the two-layer exchange flow of the estuarine circulatio to address the dynamics of residual currents at tidal and subtidal time scales (Garel and Ferreira, 2013; Stacey et al., 2001). Other dataset may support these studies, such as wind data, available from the Portuguese Sea and Atmosphere Institute (IPMA, http://www.ipma.pt).

Another example of potential data usage of global interest is the study of specific events that can significantly affect ecosystems at estuaries and coastal margins. Floods, for example, have far-reaching consequences in terms of ecology, morphology and water management. Increased knowledge of flood hydrodynamics is crucial for the formulation of robust flood risk management strategies (as required for example by the EU-FLOOD Directive). Unlike larger systems that widen significantly near their mouth, narrow estuaries (such as the Guadiana) are affected along their entire length by moderate to high freshwater inflows (FitzGerald et al., 2002). Such records from the SIMPATICO system (Figs. 2 and 3; see also Garel and Ferreira, 2011b) constitute excellent opportunities to evaluate the effects of extreme floods at larger systems where observations are rare in relation to the unexpected and hazardous nature of these events. Coastal upwellings are other examples of specific events, occurring typically between March and September along the Portuguese coast (Relvas and Barton, 2002), that are major drivers of the primary and secondary productivity along continental margins (Washburn and McPhee-Shaw, 2013).

Author contributions. O. Ferreira developed and directed the monitoring activities at the Guadiana Estuary. E. Garel maintained the station, analysed and organized the datasets, and wrote the paper. Both authors discussed the results and commented on the manuscript.

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Table 1. Summary information of the datasets from the SIMPATICO monitoring station and associated river discharge data. The column "Time-series" indicates the measurement periods separated by major data gaps (see also Fig. 2).

Data source	Instrumentation	Location	Time series	Acquisition rate	Parameters
SIMPATICO monitoring station	Multi-parametric probe (YSI 6600 V2-4)	Lower Guadiana Estuary	19 Mar 2008–15 Feb 2010 26 Jan 2012–06 Dec 2013	1 h	Temperature (°C), pH,rate dissolved oxygen ($mg\,L^{-1}$),rate turbidity (NTU), chlorophyll ($\mu g\,L^{-1}$),rate salinity (PSU) at ∼ 1 m below the water surface
SIMPATICOrate monitoring station	Acoustic Doppler ratecurrent profilerrate (Sontek Argonautrate XR)	Lower Guadianarate Estuary	19 Mar 2008–04 Jan 2010 07 Dec 2011–12 Dec 2012 02 Mar 2013–08 Apr 2014	15 min	Sensor data: near-bed temperature (°C), pressure (dbar), pitch (°), roll (°) Diagnostic data (counts): multicell beam amplitude, main cell beam noise, main cell beam strength Velocity data (east, north, vertical components, $m\,s^{-1}$): surface, main cell, multicell Standard deviation: pressure (dbar), pitch (°), roll (°), main cell velocity ($m\,s^{-1}$), multicell velocity ($m\,s^{-1}$)
Hydrographic station	Stage sensor	1. Pulo do Lobo 2. Ponte Quintos	Mar 2008–Apr 2014	1 h	River discharge ($m^3\,s^{-1}$)

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Table 2. Quality check conditions for invalidation of the ADP main-cell and multi-cell velocity data. n/a, not applicable.

Parameter	Main-cell	Multi-cell
Instrument tilting (pitch, roll)	$> 10\,^{\circ}$	n/a
Signal-to-noise ratio (SNR)	One of the 3 beams is $<$ 20 counts	The difference between the beams is $>$ 20 counts
Predicted last cell (CP)	The end of the measurement volume is 0.8 m below or above CP	Cell range equals CP, and cells above
Velocity standard deviation	$> 3\,\mathrm{cm\,s^{-1}}$ for the East and North velocity components	$> 5\,\mathrm{cm\,s^{-1}}$ for the East and north velocity components; $> 2\,\mathrm{cm\,s^{-1}}$ for the vertical velocity component
Signal strength	Mean strength of the 3 beams is 5 counts less than the mean noise	Cell where the mean amplitude of the 3 beams increases upwards, and cells above

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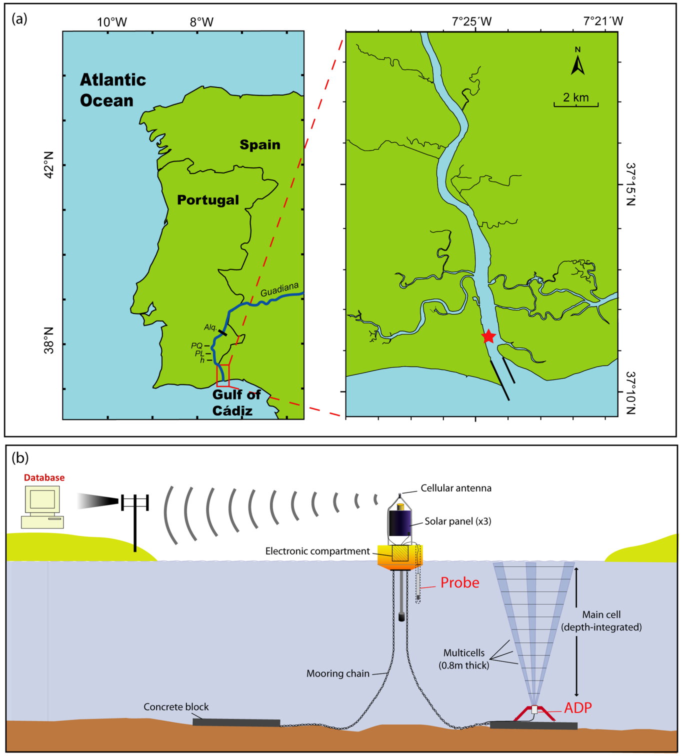

Figure 1. Location **(a)** and description **(b)** of the SIMPATICO monitoring system. The system **(a)** is located near the mouth of the Guadiana Estuary on the southern Iberian Peninsula (red star). The locations of the Alqueva dam (Alq.), estuary head (h), and Pulo do Lobo (PL) and Ponte Quintos (PQ) hydrographic stations are indicated. The equipment of the station **(b)** includes a multi-parametric probe and an acoustic Doppler current profiler (ADP).

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Multiyear high-frequency physical and environmental observations

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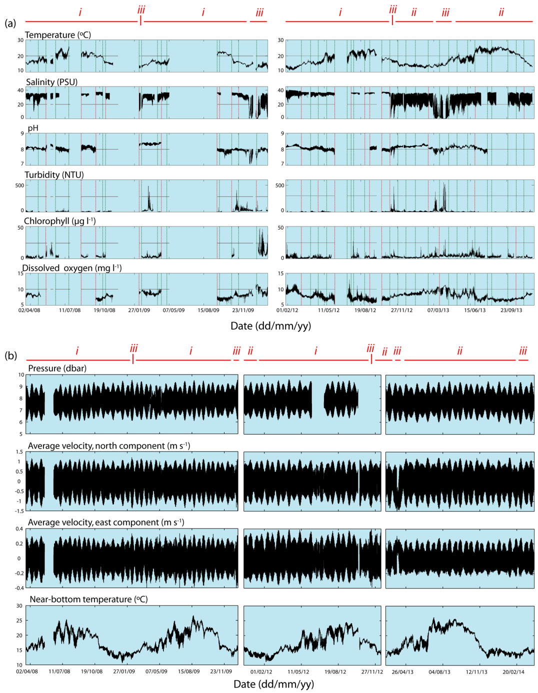

Figure 2. Time series of validated probe **(a)** and ADP **(b)** data. From top to bottom, the probe temperature, salinity, pH, turbidity, chlorophyll, and dissolved oxygen are displayed **(a)**, together with the pressure, north and east depth-integrated velocity components, and near-bottom temperature from the ADP **(b)**. In **(a)**, the time of probe cleaning and sensor calibration are indicated with the green and red vertical lines, respectively, and the raw data extent is shown with the grey horizontal lines. The periods of (*i*) zero river discharge, (*ii*) ecological flow (river discharge $\sim 50\,m^3\,s^{-1}$), and (*iii*) moderate to high river discharge ($> 400\,m^3\,s^{-1}$) are indicated in red at the top of both **(a)** and **(b)** (see also Fig. 3).

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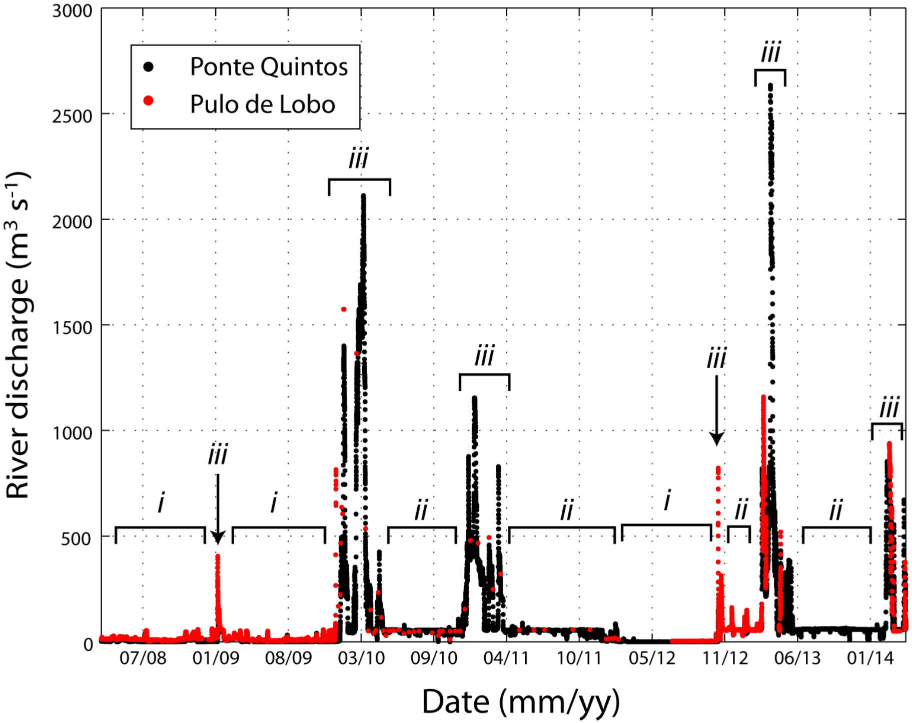

Figure 3. Freshwater discharge into the Guadiana Estuary. Hourly records (m^3 s^{-1}) from the Pulo do Lobo (black circles) and Ponte Quintos (red circles) hydrographic stations. The periods of (*i*) zero river discharge, (*ii*) ecological flow (river discharge ~ 50 m^3 s^{-1}), and (*iii*) moderate to high river discharge (> 400 m^3 s^{-1}) are indicated (see also Fig. 2).

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