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Temperature and salinity regimes in a shallow, mesotidal lagoon, the Ria Formosa, Portugal

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Abstract

In a recent study of the mesotidal Ria Formosa, a coastal lagoon in southern Portugal, water temperature in the channels ranged from 12 °C in winter to 27 °C in summer and salinity from 13 to 36.5, although much higher values were observed in saltpans. Conditions in the Ria Formosa were not homogeneous despite a large tidal exchange of water; the inner channels of the Ria Formosa were brackish in winter but hypersaline in summer. Water in inner areas of lagoon had significantly different temperature and salinity characteristics compared to the inflowing coastal water, both in winter and in summer. Areas with these differences in temperature and salinity were detectable both at low water and at high water neaps. Deterioration of water quality is therefore more probable in these areas. The waters went through a complex heating and cooling cycle in summer with diurnal difference of ~6 °C and 2 in temperature and salinity, respectively. The lack of freshwater input and high insolation meant the outflowing water of the lagoon was more saline that the inflowing coastal waters. In summer, the temperature controlled density with the least dense waters also being the most saline, whereas in winter salinity was the major density controlling parameter. The effects of these freshwater inputs were localised to the vicinity of the Gilão River. No evidence was found of persistent or widespread temperature or salinity stratification in the Ria Formosa and so this shallow lagoon appears to be vertically well mixed. Vertical mixing does not allow a dense, stagnant, bottom layer of water to form that would aggravate a deterioration of water quality. The net effect of these processes is a parcel of water that moves through the lagoon with minimal dilution and potentially receiving waste discharges.
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1. Introduction

Coastal lagoons are separated or partially isolated from oceans or seas and are saline. They may be enclosed by one or more barrier islands, as well as sand spits, and linked to the sea by one or more channels which are small relative to the lagoon (Barnes, 1977, 1980). Coastal lagoons usually run parallel to the coastline in contrast to estuaries that are normally perpendicular to the coast. Rivers may discharge into a lagoon thereby forming estuarine areas. About 13% of the world coastline is occupied by wetlands, many of which are lagoons, but in Europe only 5.3% of the coastline (2690 km) falls into this category (Barnes, 1980). Most of the lagoons in southern Europe are in the microtidal Mediterranean basin. Atlantic, mesotidal lagoons include the lagoons in south-west France and those of the western Iberian Peninsula. Lagoons naturally grade into other types of wetland habitat including semi-enclosed marine bays, freshwater lakes and estuaries (Barnes, 1980). There are two major lagoon systems in Portugal, the Ria de Aveiro in the north and the Ria Formosa on the south coast, in the Algarve.

The Ria Formosa is a large, mesotidal, coastal lagoon extending along the eastern part of the south coast of the Algarve, Portugal (36°58′N, 8°02′W to 37°03′N, 7°32′W, see Fig. 1). It is a National Park of internationally recognised importance and as such belongs to the

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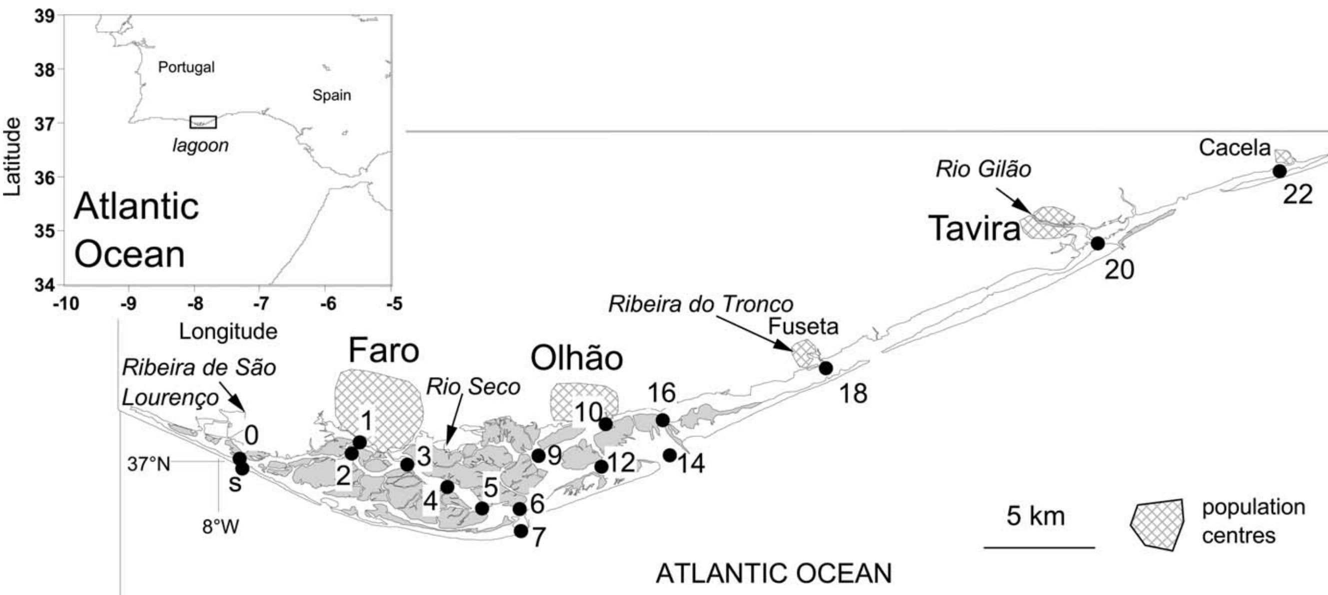

Fig. 1. Location of the Ria Formosa lagoon with sampling sites.

Ramsar Convention and Natura 2000. The role of the present paper is to describe some of the physical and ecological aspects of the Ria Formosa as well as detailing new data on the temperature and salinity regimes. Implications regarding circulation and contaminant accumulation in this and other lagoons are highlighted.

1.1. Physical and ecological characteristics of the Ria Formosa

The Ria Formosa includes a large intertidal zone, about 55 km long (E–W), and about 6 km (N–S) at its widest point (Fig. 1). This is separated from the sea by two peninsular sand spits, as well as a string of barrier islands. There are seven inlets, two of which have been artificially consolidated, that allow exchanges of water with the Atlantic Ocean. A further artificial inlet was made in the west of the lagoon in 1997 during the INDIA project. Five small rivers and 14 streams flow into the Ria Formosa but most of these dry out completely in summer. The mean annual rainfall in the Ria Formosa basin is 634 mm. Most of the rainfall occurs during the winter, often concentrated into only a few days (Instituto Hidrográfico, 1981). The most intense and frequent winds in the Ria Formosa are from the west and south-west, especially during the winter months. East and south-east winds are also quite frequent (Andrade, 1985) especially in summer when the Levante blows. The mean air temperature in summer is 25 °C and in winter 12 °C. Although the Ria Formosa is situated on the Atlantic coast, its climate is Mediterranean with hot, dry summers and warm, wet winters.

The Ria Formosa is mesotidal with a semi-diurnal tidal regime, in contrast to the Mediterranean lagoons that are microtidal (UNESCO, 1979, 1986). The tidal range varies from 1.35 m on neap tides to 3 m on spring tides (Instituto Hidrográfico, 1986). The navigable channels were extensively dredged during 2000. The average depth of the navigable channels is 6 m although most areas are less than 2 m deep. Neves (1988) has modelled the submergence and emergence period for the western part of the lagoon as a function of the tides showing that large areas of mudflats are exposed at low water but submerged at high water. Some estimates for the submerged area of the Ria Formosa are ~53 km^2 at high water and 14–22 km^2 at low water (after Águas, 1986) with a maximal tidal volume of 140×10^6 m^3 (after Instituto Hidrográfico, 1986). The coefficient of renovation (Volume of HW − Volume of LW/Volume of LW) for the lagoon is 3.2 for a spring tide and 1.0 for a neap tide (Águas, 1986). Between 50 and 75% of the water in the lagoon is exchanged daily by the tides. The flood current velocity at the Barra do Farol (main inlet southeast of Faro) is 0.4 m s^{-1} and the ebb current velocity is 0.8 m s^{-1} at neap tides. The respective values are 0.3 and 0.2 m s^{-1} at the much smaller Barra de Ancão to the west (Lima & Vale, 1980). The currents measured further up the channels are much weaker than at the inlets (Lima & Vale, 1977). Near the port at Faro the current velocity during the ebb is 0.56 m s^{-1}, whereas near the port of Olhão it is 0.66 m s^{-1} at the flood (Instituto Hidrográfico, 1979) again at neap tide.

The National Park comprises 78,000 ha including a 10,000 ha coastal lagoon with 5000 ha of salt marsh and mud flats, as well as 2000 ha of sand banks and dunes and a further 1000 ha of saltpans and aquaculture ponds (CCRA, 1984). The lagoon is a complex network of channels, some of which are navigable to the ports of

Faro, Olhão and Tavira. Various theories have been proposed to explain the development of the Ria Formosa and are summarised in Andrade (1985) and Batty (1991). The lagoon system is highly dynamic and historical maps are summarised by Falcão, Pissara, and Cavaco (1991). The different habitats in the Ria Formosa support a rich diversity of flora and fauna. Studies of the biology of the lagoon organisms include Baptista (1993), [Micro-organisms]; Assis, Sampayo, and Vilela (1984), [Phytoplankton]; Vilela (1965) and Silva and Assis (1970), [Plankton]; Cunha and Massapina (1984) and Gonçalves, Sousa Reis, and Sacadura Monteiro (1988), [Zooplankton]; Gamito (1989) and Sprung (1994), [Benthic community]; Austen, Warwick, Rosado, and Castro (1989), [Meio and macrobenthic community]; Aliaume, Monteiro, Louis, Hoia, and Lasserre (1993), Monteiro, Hoai, and Lasserre (1987), and Monteiro, Lasserre, and Hoai (1990), [Fish]; Duarte, Sousa Reis, Sacadura Monteiro, and Gonçalves (1988), [Macrophytes]; Simões (1984a,b), [Dune vegetation]. Earlier articles are reviewed in Andrade (1985). The Ria Formosa is ecologically important due to its role as a stopping place for migratory birds (Batty, 1991) and a breeding ground and nursery for many species of fish and molluscs (Andrade, 1985). Fifty-five species of fish and a great variety of bivalves have been identified in the lagoon. The most important commercial bivalves are *Venerupis decussata*, the crosscut carpet shell, and *Cerastoderma edule*, the common cockle.

The Ria Formosa lagoon is an important ecosystem but also a valuable regional resource for tourism, fisheries, aquaculture and salt extraction industries. The urban development around the lagoon places increasing pressure on this sensitive system (Icely, 1987) and compromises the water quality of the lagoon, (Bebianno, 1995; Durham, 2000; Mudge & Bebianno, 1997; Newton, 1995; Newton & Mudge, submitted for publication).

As part of a major study of the lagoonal system, the temperature and salinity regimes were investigated at timescales ranging from tidal to annual. The primary objective of the general survey was to identify areas within the lagoon where the characteristics of the water were significantly altered in comparison to the inflowing coastal seawater; inadequate tidal flushing in such areas may lead to deterioration of water quality, particularly in the summer months (Bebianno, 1995; Durham, 2000; Mudge & Bebianno, 1997; Mudge, Bebianno, East, & Barreira, 1999; Newton, 1995).

2. Materials and methods

In situ measurements of temperature and salinity were made at 1-m depth intervals through the water column using a temperature and salinity bridge (ST Bridge MC5, Electronic Switchgear London Ltd, Nat. Inst. Ocean.). The instrument was calibrated in the laboratory before fieldwork using a laboratory thermometer and standard seawater.

To give good spatial coverage, as well as representing the variety of conditions to be experienced within the Ria Formosa, a subset of 16 sampling stations were chosen from a larger survey of 22 stations (Fig. 1). The criteria used in the selection of these stations are listed below.

- Some stations at the seawater inlets were chosen to represent the seaward boundary conditions (stations 7 and 14).
- Some stations near the ends of the channels were chosen to represent the blind ends of the lagoon (stations 0 and 22).
- Some stations located close to towns were selected to represent areas subject to domestic sewage inputs (stations 1, 9, 10 and 18).
- A station was chosen close to the mouth of the only large river flowing into the system to represent areas subject to freshwater inputs (station 20).
- Some stations located along the channels were chosen, from the inner lagoon to the seaward boundary, to represent intermediate situations (stations 2–6, 12 and 16).

Data were collected from the stations monthly from June to May (1988/9) inclusive. In order to maximise comparability of the monthly data sets, all sampling dates were chosen to coincide with neap tides, when tidal flushing was low and possible deterioration in water quality most likely to be apparent. Tidal effects were assessed by sampling at high water and low water.

One station (station 0) was selected for an intensive study of tidal cycles (24 h) and an annual study with weekly sampling. The station was chosen because it is an important area for bivalve culture and recreational waters. It is also equidistant from the main sewage outlets of Faro and one of the seawater inlets. Three consecutive days in September, coinciding with the maximum tidal ranges for the year, were studied for the tidal cycle surveys (12 h, daytime). Temperature and salinity were determined in situ at 15-min intervals. A 24-h cycle over a neap tide was also studied. During these observations, temperature and salinity measurements were also taken from station S, the nearby seashore, every 3 hours to provide background information on the seawater boundary conditions.

3. Results

3.1. Spatial survey

The annual average temperature of the waters in the lagoon ranged from 18.1 °C near the Armona inlet to

20.6 °C at Faro. The average salinity ranged from 31.5 at station 20 which is exposed to freshwaters from the Gilão River to 35.4 at the seawater inlets. A previous study found temperatures in the lagoon water of the Ria Formosa ranging from 11.9 to 27 °C (CEPASA, 1980). Salinity in the main channels of the Ria Formosa ranged from 12.7 (Instituto Hidrográfico, 1989) to 36.5 (Cunha & Massapina, 1984) although much greater values are possible during the summer in salt pans and inner areas of the lagoon.

The general hydrography of the Ria Formosa under winter and summer conditions, as well as the variation within the lagoon, are discussed with respect to the data collected in August (summer regime) and November (winter regime). The November data were chosen to illustrate the winter condition as it is the most complete winter data set and shows the main characteristics of winter situation. The November data are discussed first because they are similar to normal, estuarine conditions. The August data set illustrates typical summer conditions in the Ria Formosa, which are somewhat unusual for most lagoons as the high evaporation rate leads to reverse estuarine behaviour. Figs. 2–5 show the distribution of the temperature, salinity and density of the lagoon under the different tidal and seasonal regimes. The horizontal axis is the station number. Since the sampling stations are not equally spaced, gradients in the eastern part of the lagoon (stations 18–22) appear accentuated.

3.1.1. Winter conditions (November, neap tide, dry day)

The high water, winter situation is shown in Fig. 2. The temperature distribution is shown in Fig. 2a when the mean water temperature for the lagoon was 18.3 °C; the maximum water temperature (19 °C) was observed at the seawater inlet (station 7) whereas the minimum temperature (16.4 °C) was observed at the shallow stations near channel ends (0 and 22). The temperature gradients were strongest at station 3, a relatively central location (0.44 $°C\,km^{-1}$) and at station 9, in the Olhão channel. The water near the Gilão Estuary (20) was close to the average temperature (18.4 °C).

The mean salinity for the lagoon (Fig. 2b) was 35.25. The maximum salinity (35.7) was observed at the seawater inlet (7) at 4 m depth; the minimum salinity (32.1) was observed in Gilão Estuary (20) as a result of inflowing freshwater.

The density distribution derived from the above temperature and salinity data is shown in Fig. 2c. The mean density for the lagoon was 1025.4 $kg\,m^{-3}$. The maximum density observed was 1025.8 $kg\,m^{-3}$ at the shallow station near end the of the east channel (22). The minimum density observed was 1023 $kg\,m^{-3}$ in the Gilão Estuary (20). The water density appears to mirror that of the salinity and therefore it is suggested that the density distribution is primarily controlled by the salinity.

The low water, winter situation is shown in Fig. 3. The temperature distribution shown in Fig. 3a is similar to the high water condition. Relatively cool water was found in the shallow areas of the lagoon near stations 1 and 2, probably due to surface cooling. As before, the greatest temperature gradient was close to station 3. The observations showed no evidence of thermal stratification.

The salinity distribution is shown in Fig. 3b. The mean salinity for the lagoon was 34.64. As expected, the maximum salinity (35.7) was observed at the seawater inlet (7). The minimum salinity (26.84) was observed at the shallow station near the end of the west channel (0) and in the Gilão Estuary (20). Stations 3–16 were effectively homogenous with respect to salinity. Strong salinity gradients were observed between stations 0 and 3 and near the Gilão Estuary at station 20.

The density distribution is shown in Fig. 3c. The mean density for the lagoon was 1025 $kg\,m^{-3}$. The maximum density (1025.7 $kg\,m^{-3}$) was observed at the seawater inlet (7); the minimum density (1019.2 $kg\,m^{-3}$) was observed at the Gilão Estuary (20) and at the shallow west end of the lagoon, close to the São Lourenço River (0). Stations 3–16 were homogenous with respect to density confirming that the Ria Formosa lagoon density was primarily controlled by the salinity distribution in November. The waters were vertically well mixed with no density driven mixing likely.

Temperature and salinity data for high water and low water collected throughout the lagoon in November are summarised in Table 1. The temperature range in winter was small (2.6 °C at high water), with the warmest water at the seawater inlet (station 7) and the coolest water in the shallow, inner channel to the east (22). The salinity range was greatest (8.8 at low water) with the most saline water at the seawater inlet and the least saline water at the shallow, inner channel to the west near the Ribeira de São Lourenço stream (0) and also near the Rio Gilão (20). The lagoon was estuarine in winter with the inflowing seawater more saline than the lagoon water. The water column was generally well mixed, with sharp 'fronts' at station 3 delineating the boundary between 'inner' and 'outer' lagoonal water masses. The 'outer' lagoonal water was well flushed by the tide and almost homogenous up to station 3. In contrast, cooler, lower salinity water was found in the 'inner' parts of the lagoon, especially near streams and rivers (stations 0 and 20) although the density structure was essentially salinity controlled.

3.1.2. Summer conditions (August, neap tide, dry day)

The high water, summer situation is shown in Fig. 4. The temperature distribution is shown in Fig. 4a: the mean water temperature for the lagoon was 21.6 °C and the temperature maxima (26 °C) were observed near Faro (at station 2) and Olhão (at station 10) and also

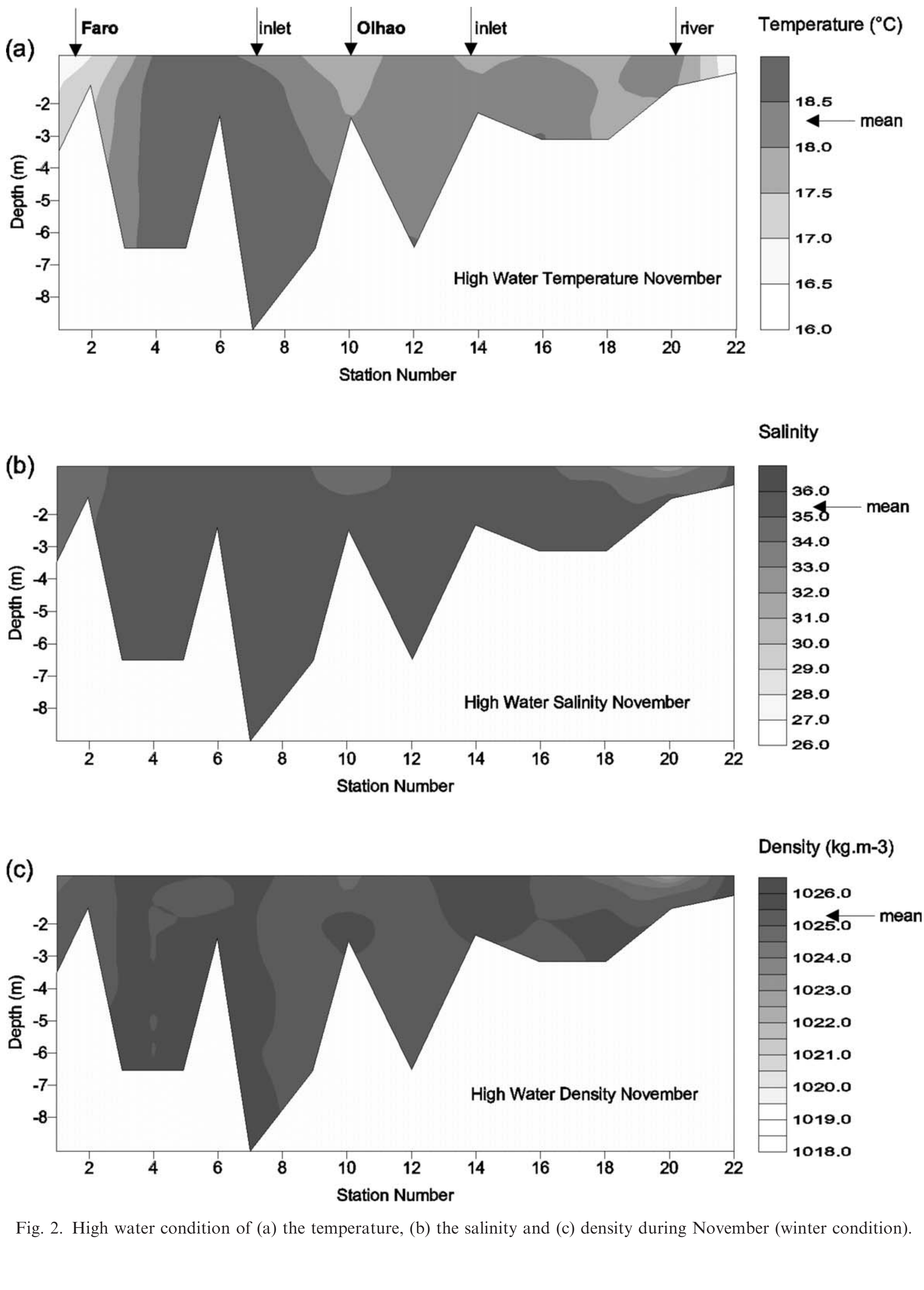

Fig. 2. High water condition of (a) the temperature, (b) the salinity and (c) density during November (winter condition).

at stations 16, 18 and 22. The minimum temperature (18.8 °C) was observed at the seawater inlets (7 and 14) in the deeper water. The temperature of this deep seawater was almost identical to the winter situation. The stations in shallow parts of the lagoon were warmer (depth averaged) than the deeper waters in the navigable channels. The greatest temperature gradients were found at stations 3, 9, 12–14, 14–16, which are the boundaries between the 'inner' and 'outer' lagoon. There was little evidence of stratification although the observations at the inlets indicated that the flood water first penetrates the lagoon at depth.

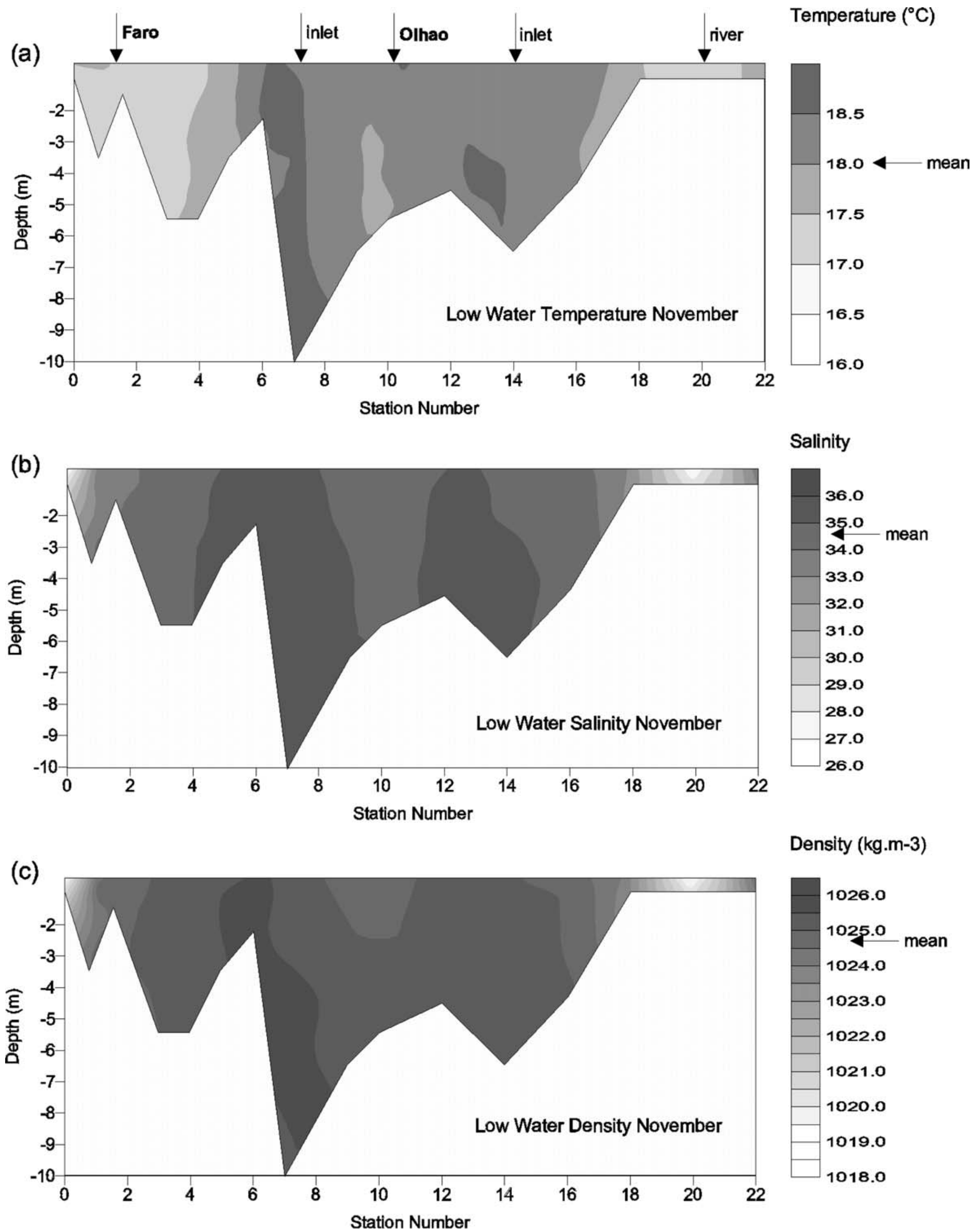

Fig. 3. Low water condition of (a) the temperature, (b) the salinity and (c) density during November (winter condition).

The salinity distribution is shown in Fig. 4b. The mean salinity for the lagoon was 35.47. The maximum salinity (36.15) was observed at the shallow west end of the lagoon (0). The minimum salinity (35.2) was observed in the inflowing seawater (inlets 7 and 14). Maximum salinity gradients were observed at station 3 and also between stations 9 and 10.

The density distribution is shown in Fig. 4c. The mean density for the lagoon was 1024.7 $kg\,m^{-3}$. The maximum density (1025.3 $kg\,m^{-3}$) was observed near the seawater inlet (6 and 7, deep water). The minimum density (1023.6 $kg\,m^{-3}$) was observed in the surface waters at stations 2 and 10. High temperatures compensate for high salinities and the temperature controls the

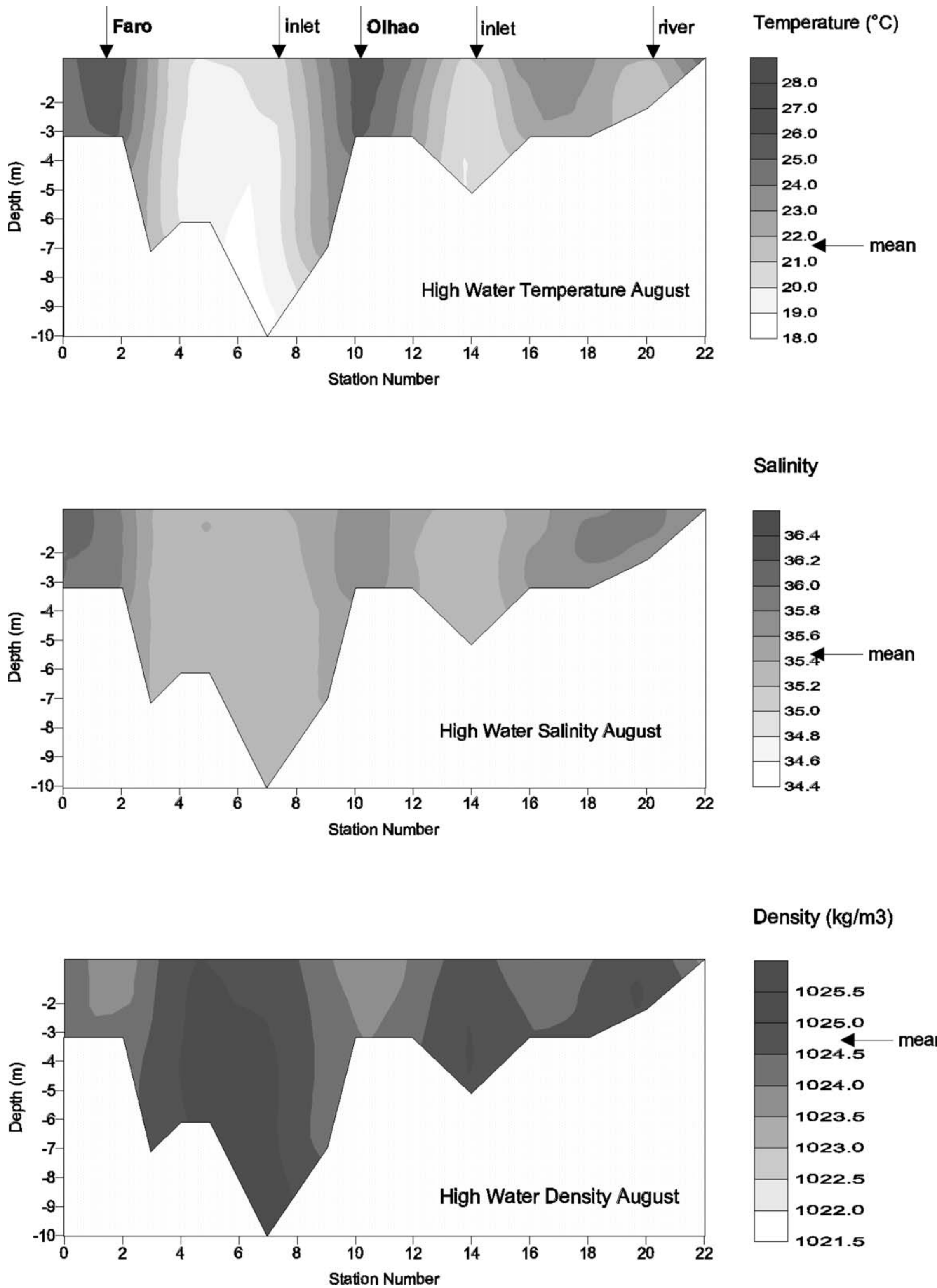

Fig. 4. High water condition of (a) the temperature, (b) the salinity and (c) density during August (summer condition).

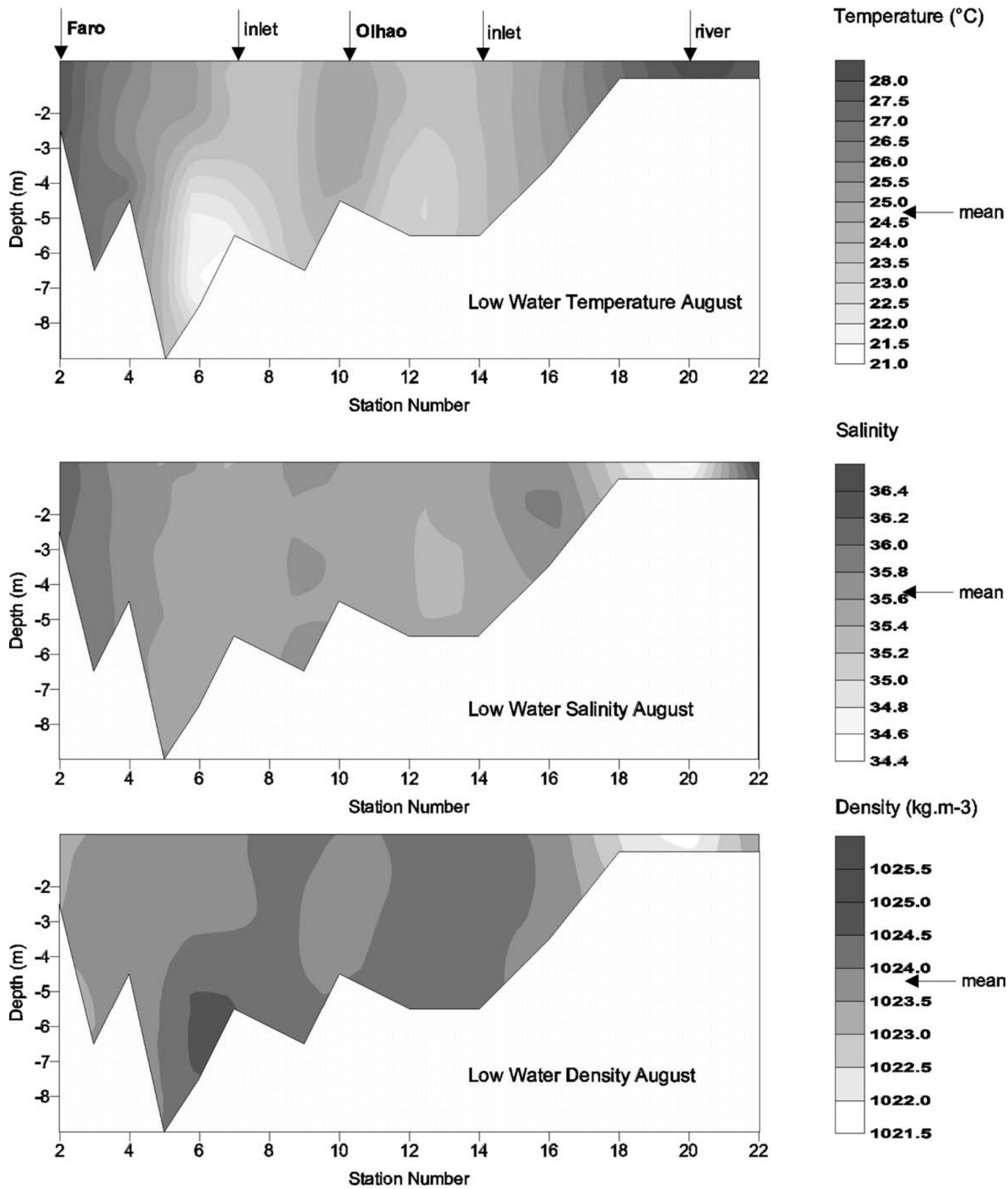

Fig. 5. Low water condition of (a) the temperature, (b) the salinity and (c) density during August (summer condition).

density in this case. The waters between stations 0 and 2 have the most saline waters although they are the least dense of the system at this time.

The low water, summer situation is shown in Fig. 5. The temperature distribution is shown in Fig. 5a. The mean water temperature for the lagoon was 24.75 °C; the maximum water temperature (28.4 °C) was observed at station 2 and near the Gilão Estuary (20) and the minimum water temperature (21 °C) was observed in the outflowing water at depth (7). The maximum temperature gradient was observed between stations 2 and 5.

The salinity distribution is shown in Fig. 5b. The mean salinity for the lagoon was 35.6. The minimum salinity (34.45) was observed near the Gilão Estuary (station 20). The salinity maxima (36.45) were observed at stations 2 and 22. This range is small especially when compared to estuaries or other lagoons where the freshwater input is greater. The observations did not indicate any salinity stratification in the lagoon.

The density distribution is shown in Fig. 5c. The mean density for the lagoon was 1023.9 kg m^{-3}. The localised inflow of warm, low salinity water from the Gilão

Table 1
Summary of winter and summer temperature and salinity across all lagoonal sites

	Temperature (°C)			Salinity		
	Min.	Max.	Range	Min.	Max.	Range
HW (Nov)	16.4	19	2.6	32.1	35.6	3.5
HW (Aug)	18.8	26	7.2	35.2	36.15	1
LW (Nov)	17	18.6	1.6	26.8	35.6	8.8
LW (Aug)	21	28.4	7.4	34.45	36.45	2

River (20) was the most obvious feature and temperature appeared to be controlling the density distribution.

The temperature and salinity data for high water and low water collected throughout the lagoon in August are summarised in Table 1. The temperature range in summer was greater than in winter (7.4 °C at low water), with the coolest water at the seawater inlet and the warmest water in the shallow, inner channels to the west and east of the lagoon. The salinity range was smaller than in winter (2 at low water) with the most saline water in the shallow, inner channels to the west and east and the least saline water near the Rio Gilão. The water column was generally well mixed, with the same sharp 'fronts' delineating the boundaries between the 'inner' and 'outer' lagoonal water masses. The density structure was temperature controlled in August.

4. Discussion

4.1. Effect of freshwater and seawater inflow

The temperature and salinity diagrams (Figs. 2–5) showed that seawater inflow influences the 'outer' lagoon that has marine characteristics. Previous analyses of sterol and fatty acid biomarkers (Mudge et al., 1999; Mudge, East, Bebianno, & Barreira, 1998) have indicated the presence of diatoms in the major inlets with a different mixed population in the inner sections of the lagoon. Residual water in the lagoon at low water had different temperature and salinity characteristics to the inflowing seawater, indicating that tidal flushing was incomplete at neap tides. The effect of the inflowing seawater during neaps reached to between stations 3 and 4 in the case of the Faro channel, but the water at stations further up this channel (2, 1, 0) had different properties. The water characteristics of the Ria Formosa were mainly controlled by the effect of the tidal inflow of coastal water which spread up the channels. The temperature of the inflowing seawater in November (18.4 °C) was not very different from the temperature of the deep inflow in August (18.8 °C) although lower temperatures (15 °C) were observed in late winter (February, Newton, 1995). The effect of freshwater inflow, such as the Gilão River, was localised, especially in summer.

4.2. Stratification

Most stations showed only weak, or no, thermal stratification. The summer data showed some evidence of a multi-layer system at the seawater inlet (station 7) with the cooler, less saline seawater penetrating the lagoon at depth while the warm, saline waters of the lagoon flow out at the surface. Durham (2000) indicates that, after the opening of the new inlet in 1997, there may now be some stratification in the western end of the Ria Formosa. If stratification does occur, bottom waters may be isolated from the atmosphere and, due to oxygen usage by algae and bacteria, anoxia may develop.

4.3. Seasonal cycling

The T–S diagram for surface coastal waters and station 0 is shown in Fig. 6a. The annual cycle for coastal water begins in January (at *a* in Fig. 6a). *a* to *b* is the gradual warming of coastal waters with a corresponding

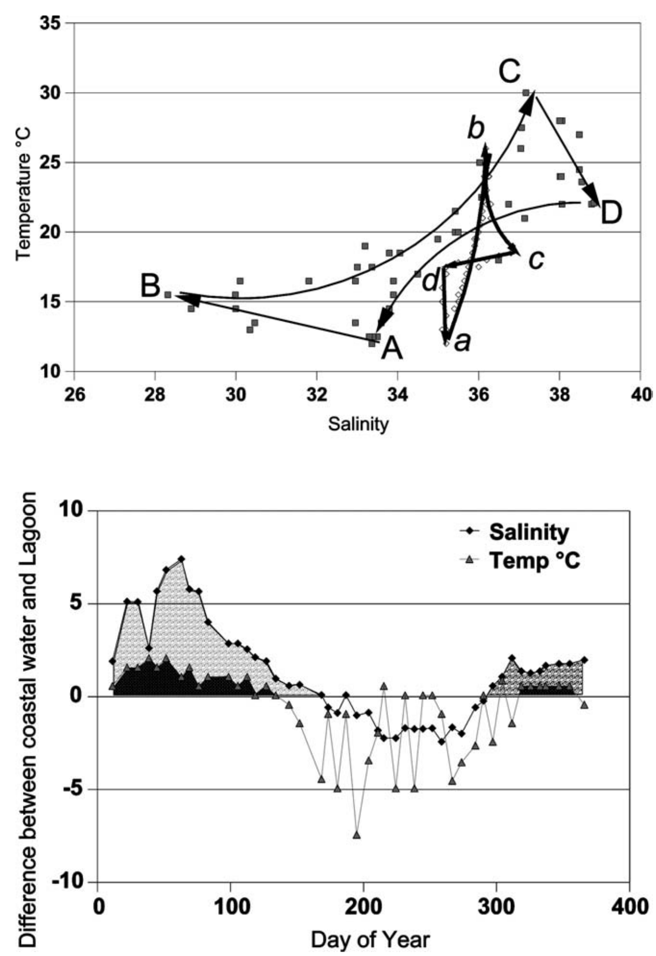

Fig. 6. (a) The T–S diagram for the open coastal waters (*a–d*, dashed line) and inner lagoonal water (*A–D*, solid line) for 1 year. *Aa* is January and *Cb* is July. (b) The difference in temperature and salinity between the open coastal water and inner lagoonal water for the same period. ♦, salinity; △, temperature (°C).

increase in salinity reaching a maximum in late July. *b* to *c* represents early autumn cooling, although the salinity continues to increase slightly. *c* to *d* indicates an abrupt decrease in salinity, but not temperature, probably due to a change in water mass or vertical mixing of the offshore waters in early autumn. In late autumn, *d* to *a*, the water cools with no concurrent change in salinity.

The annual cycle for the lagoonal water starts in January at *A*. *A* to *B* (March) represents a decrease in salinity due to freshwater runoff into the lagoon. *B* to *C* is indicative of the heating and evaporative processes prevalent in the spring and summer that form the warm, hypersaline waters of the summer months. *C* to *D* represents early autumn cooling, although the salinity continues to increase slightly. *D* to *A* represents autumn and winter cooling and dilution by freshwater runoff into the lagoon.

The difference in temperature and salinity between the coastal water and station 0 is shown in Fig. 6b. The lagoon water was cooler than the coastal water until mid-May and again from mid-November; this is probably due to freshwater inputs and more rapid heat exchange of the shallower waters (cooling in winter, heating in summer) compared to the deeper offshore water masses. The lagoon water was less saline than the coastal water until mid-June and again from mid-October again due to freshwater input over winter and also evaporative water losses in summer. The temperature difference during the summer months (mid-May to mid-September) had a pronounced 'saw-tooth' pattern due to the time of sampling (early morning or mid-afternoon) and implies that the water entering the lagoon increased in temperature by about 5 °C during its daytime residence in the system.

4.4. Tidal cycling

Fig. 7 shows the surface salinity and temperature variations during equinoctial spring tides in September on three consecutive days at station 0. The data are plotted relative to the time of high water. Temperature variation throughout the day at station 0 is shown in Fig. 7a. The temperature of the water increased from 20 °C at 08:30 reaching 24 °C by 21:00. The temperature increase slowed towards high water as a consequence of the input of relatively cool ocean water. A small 'peak' in temperature (23 °C) was also recorded just after high water at the beginning of the ebb coincident with the peak in the salinity observations (Fig. 7b). This suggests that a patch of hypersaline, warm water flowed past station 0 at the start of the mid-afternoon ebb.

Salinity variation throughout the day is shown in Fig. 7b. As the tide floods into the lagoon the salinity decreases from 38.5 to 37 because the inflowing seawater is still less saline than the hypersaline lagoon water. Salinity then increases throughout the ebb. All three cycles showed a small increase in salinity to 37.4 shortly after high water. The small peak occurred 30 min after high water on the three consecutive days. This implies that there was a source of hypersaline water that flowed past station 0 as a 'patch' shortly after the start of the ebb. This could be water draining off the channels of the salt marsh behind the dyke which leads to Faro bridge or brines from the São Lourenço salt extraction pans, 1.5 km to the west.

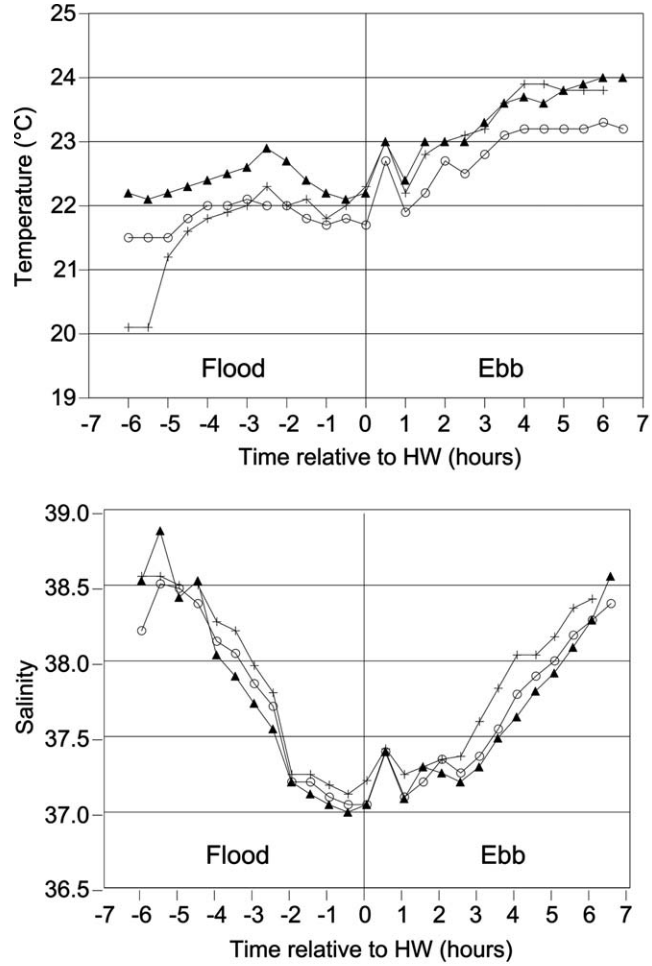

Fig. 7. (a) The temperature and (b) salinity for three consecutive daytime tides in September plotted relative to the time of high water (early afternoon). +, 27 September; ○, 28 September; ▲, 29 September.

A T–S diagram for the 25 h neap cycle on 22 and 23 September is shown in Fig. 8. The cycle starts at A, mid-afternoon at low water, with warm, hypersaline water ebbing from the inner lagoon. AB is the decrease in temperature and salinity during the evening flood as the ocean water is cooler and less saline reaching high water at B. BC is the continued cooling during the night time ebb until C, the low water at dawn; the salinity increases due to the draining of the hypersaline water from the inner lagoon. CD and DE represent the morning flood with high water at E; the salinity decreases initially and then increases throughout the rest of the day closing the

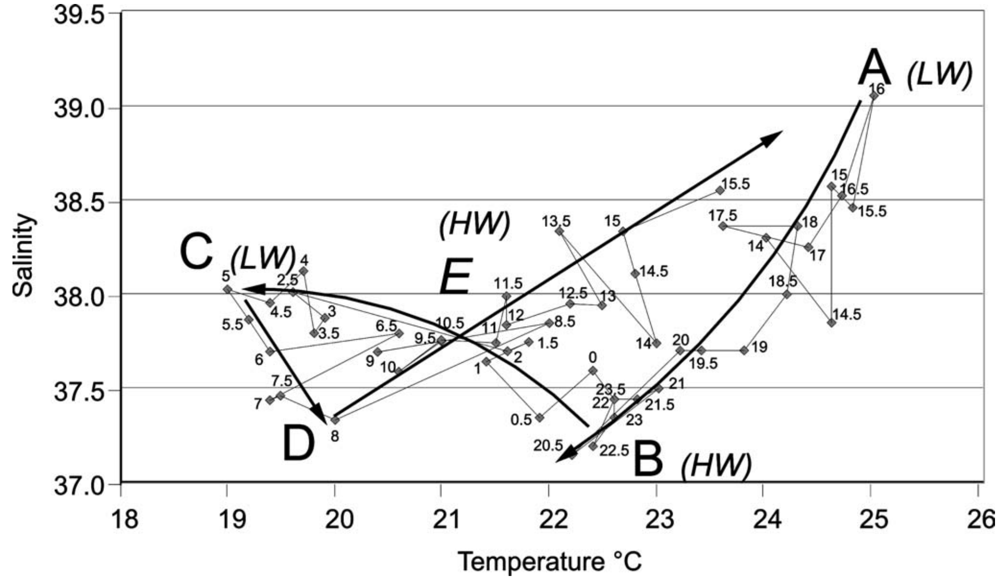

Fig. 8. A T–S diagram for a full 25 h neap tidal cycle. The points are labeled with the sampling time.

cycle at A. The temperature increases throughout the day and so the waters of the afternoon ebb (EA) were warm and hypersaline. Therefore, the diurnal temperature and salinity ranges are ~6 °C and 2, respectively.

Fig. 9 shows the salinity at station 0 plotted against water temperature through a spring tidal cycle (12 h). Two other such cycles for the following days were also studied but are not shown for clarity. At low water in the morning (A), the residual water flowing past station 0 is hypersaline but cooled during the night so that the temperature is relatively low. During the morning flood, the temperature increases due to solar heating but the salinity decreases as less saline water flows into the lagoon. The salinity minimum is reached just before high water (B). The data indicate that the ocean water may arrive at station 0 in two separate pulses, the first probably from Barra de Ancão inlet. Before the arrival of the second pulse, probably from the more distant Barra do Farol inlet, a patch of relatively warm and saline water washes past station 0 at HW-0.5. This is presumably flushed up the channel between the town of Faro and station 0 by the arrival of the tide through the Barra do Farol.

During the late afternoon ebb, the temperature and salinity increases as water that has been heated and subject to evaporation in the shallow channels to the west

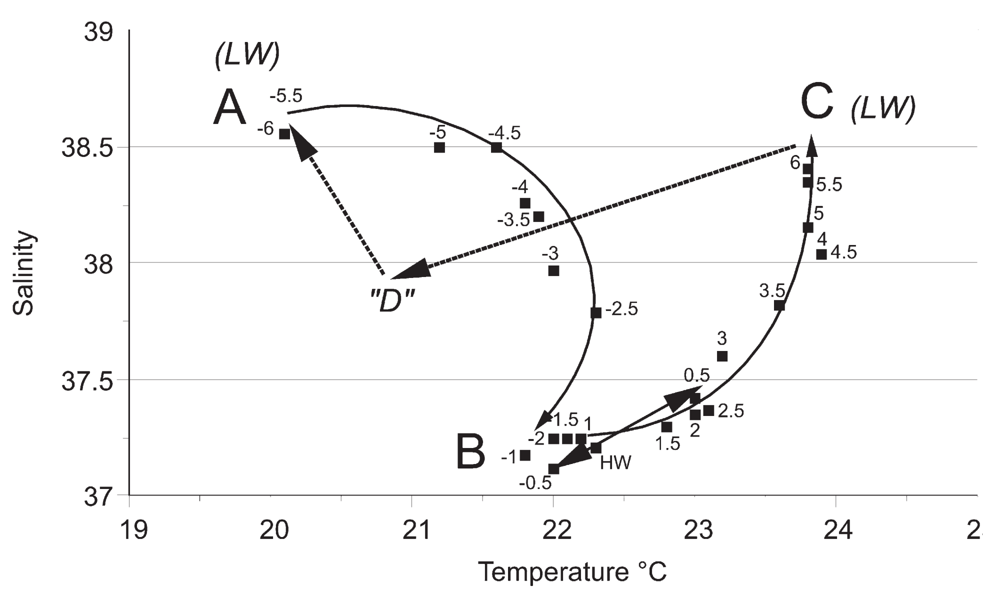

Fig. 9. A T–S diagram for a 12 h spring tidal cycle with the suggested behaviour indicated by dashed lines. The points are labeled relative to the midday high water time; negative numbers are for the flood and positive for the ebb.

flows past station 0 (BC). The temperature is principally controlled by the time of day rather than the state of the tide whereas salinity is largely controlled by the tide.

Although the sampling was not conducted overnight, we can postulate that the salinity and temperature will be controlled by similar processes such that the waters will cool overnight becoming less saline due to the influx of seawater (CD). They will return to the initial hypersaline condition with minimal extra cooling during the nighttime ebb (DA). These processes are indicated by the dashed lines in the figure.

Given these data, it is possible to postulate the flows in the western end of this lagoon that has a series of tortuous channels by which water may enter and leave the system. In a schematic diagram of the system (Fig. 10), the sequence of events may be summarized:

1. Water flows into the system through both the Barra de Ancao and the Barra do Farol. There is no effective internal link between these two inlets and so the water passes up the channels towards Faro and the Ancao basin.
2. Water from the previous tide (shaded) in the Ramalhete channel near Faro is backed up behind this incoming seawater and is pushed towards the Ancao basin. This plug is responsible for the pulse of warm saline water seen prior to high water. Repeated CTD records from station 0 (Durham, 2000) also show this pulse of water passing into the basin.
3. At high water, the water in the Ancao basin becomes warmer and more saline as the day progresses.
4. By the beginning of the ebb, this water has reached maximum salinity and temperature as seen in Fig. 4.
5. The water ebbs out of the basin through the Ramalhete channel towards Faro and through the Barra de Ancao to the open ocean.
6. The seawater that entered through the Barra do Farol is pushed back out although recent evidence (Lencart, unpublished data) suggests ~10% less exits through this route than entered.

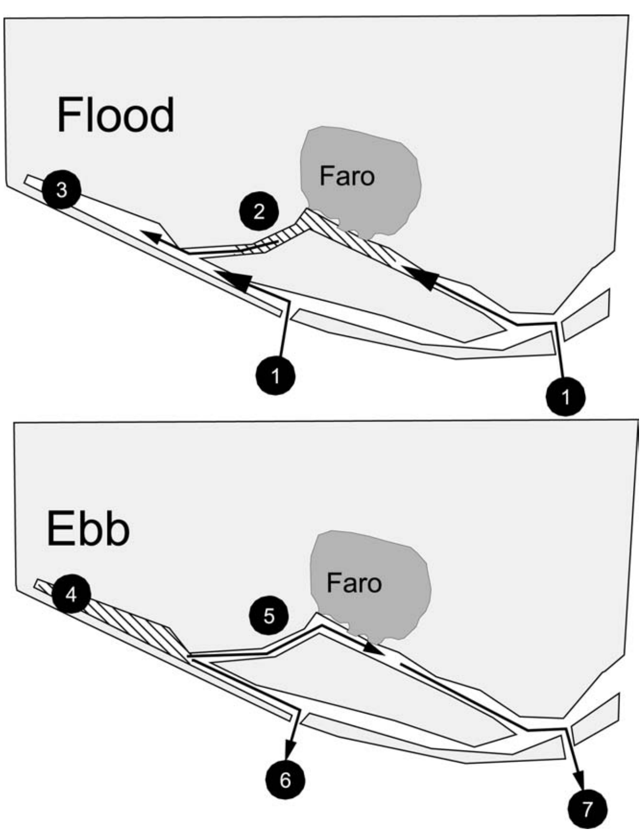

Fig. 10. A schematic diagram indicating the tidal movements through the western portion of the Ria Formosa lagoon. The numbers refer to stages of the cycle and are explained in the text.

5. Conclusions

The Ria Formosa lagoon is situated on an Atlantic coast in a Mediterranean climatic region. The hot, dry summer weather heats the water increasing its temperature, evaporation and salinity. The winter is cooler and rainfall dilutes the lagoon with freshwater so that the water temperature and salinity decrease. The Ria Formosa is tidal because it is on an Atlantic coast, in contrast to Mediterranean lagoons. However, the exchange of water is restricted to the seven inlets making the lagoon a region of restricted exchange.

During these surveys, the Ria Formosa was brackish in winter but the lagoon was hypersaline in summer. Conditions in the Ria Formosa were not homogeneous despite the large tidal exchange of water. The coefficient of renovation suggests 75% of the water may be exchanged daily, however, this may be the same 75% each day with little mixing between the 'inner' and 'outer' lagoonal water masses. Water in 'inner' areas of the lagoon had different temperature and salinity characteristics compared to the inflowing coastal water, both in winter and in summer. These differences in temperature and salinity are detectable both at low water and at high water neaps. Deterioration of water quality is, therefore, more probable in these areas. The effects of freshwater inputs are ephemeral and are localised to the Gilão River. No evidence was found of persistent or widespread temperature or salinity stratification of the Ria Formosa although more recent data may suggest this is occurring in the inner regions (Durham, 2000). Vertical mixing prevents a dense, stagnant, bottom layer of water forming that would aggravate any deterioration in water quality and so further study of this phenomenon is in progress.

These results highlight the danger in thinking that large tidal exchanges mean water quality will not deteriorate; if the inflowing waters to regions of restricted exchange such as coastal lagoons, embayments and fjords do not mix with the semi-permanent 'inner' waters, nutrient concentrations are likely to increase (e.g. Newton & Mudge, submitted for publication) and low oxygen conditions may occur. The results would negatively impact on tourism, fisheries and the amenity value of the system.

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