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Residence times in a hypersaline lagoon: Using salinity as a tracer

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Abstract

Generally the waters of the Ria Formosa Lagoon, Portugal have a short residence time, in the order of 0.5 days (Tett, P., Gilpin, L., Svendsen, H., Erlandsson, C.P., Larsson, U., Kratzer, S., Fouilland, E., Janzen, C., Lee, J., Grenz, C., Newton, A., Ferreira, J.G., Fernandes, T., Scory, S., 2003. Eutrophication and some European waters of restricted exchange. Continental Shelf Research 23, 1635–1671). This estimation is based on the measurements of currents and the modelling of water exchange at the outlets to the ocean. However, observations of the temperature and salinity in the inner channels imply that residence time is greater in these regions of the lagoon. To resolve this apparent contradiction, spatial measurements of the temperature and salinity were made with a meter for conductivity, temperature and depth along the principal channels of the western portion of the lagoon, with a sampling frequency of two per second. Evaporation rates of 5.4 mm day^{-1} were measured in a salt extraction pond adjacent to the lagoon and used to determine the residence time through salinity differences with the incoming seawater. In June 2004, the water flooding in from the ocean had an average salinity of 36.07 which contrasted with a maximum of 37.82 at mid ebb on a spring tide, corresponding to a residence time of >7 days; the mean residence time was 2.4 days. As the tide flooded into the channels, the existing water was advected back into the lagoon. Although there was a small amount of mixing with water from another inlet, the water body from the inner lagoon essentially remained distinct with respect to temperature and salinity characteristics. The residence time of the water was further prolonged at the junction between the main channels, where distinct boundaries were observed between the different water masses. As the water ebbed out, the shallow Western Channel was essentially isolated from the rest of the outer lagoon, and the water from this channel was forced down the Ramalhete Channel, from where it was unable to exit the lagoon in one tidal cycle due to the extensive path length of ~14 km to the sea.

Although the overall exchange rate of water is short in the outer lagoon, this study emphasizes that management models should take into account additional complexities that might arise from the much longer exchange rates of the inner lagoon. For example, the principal sewage discharge for the urban area of Faro is into the section of the Ramalhete Channel where efficient flushing is impeded by the relatively high residence times of the water body in this channel.

The implementation of the techniques used for this study are a quick and relatively cost effective approach to testing assumptions about water quality and exchange in shallow coastal systems.

Keywords: lagoon; salinity; temperature residence time; flushing time; evaporation rate

1. Introduction

Coastal zones contribute significantly to the life support systems of most societies (LOICZ, 2005). However, sheltered areas such as lagoons form a complex transition between terrestrial and marine aquatic environments that are particularly vulnerable to anthropogenic hazards. Some lagoons have a low freshwater input confined to the winter months whilst, during the rest of the year, the dry arid conditions of the hinterland lead to no or very low freshwater inputs and high evaporative losses from the surface waters (Newton and Mudge, 2003). As lagoons have a restricted exchange with the sea (Tett et al.,

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2003), the waters of the system can have salinities in excess of the incoming seawater to produce hypersaline conditions. The Ria Formosa in southern Portugal on the Atlantic coast (Fig. 1) is a good example of a hypersaline lagoon, but there are others around the world including: San Quintin, Mexico (Camacho-Ibar et al., 2003); Puttalam, Sri Lanka (Arulananthan et al., 1995); Almeria, Spain (Esteban and Finlay, 2003); Lagoa Vermelha, Brazil (Elias et al., 1997); Muni Lagoon, Ghana (Gordon, 2000); Shark Bay, Australia (John, 1991); and Tomales Bay, Mission Bay and San Diego Bay, CA, USA (Largier et al., 1997).

In the case of Europe, management and environmental protection of lagoons comes within the scope of the Water Framework Directive (WFD) of the European Union (EU), where the management strategies are based on the typology of the water system (CEC, 2000). For example, ‘‘transitional waters’’ such as estuaries are partly saline but are substantially influenced by freshwater, whilst ‘‘coastal waters’’ include the area one nautical mile from the coastal baseline and the outer limit of ‘‘transitional waters’’ (McLusky and Elliot, 2007). However, within these definitions, there are specific problems implementing management strategies for coastal areas with restricted exchange, such as lagoons. Under the Common Implementation Strategy of the WFD, the mesotidal Ria Formosa lagoon has been classed as a very sheltered, shallow, coastal water due to the absence of significant freshwater inflow (Newton et al., 2003). Water exchange is, therefore, fundamental to the quality of the lagoon water, a parameter that has been considered in a number of studies (references in Nobre et al., 2005). The historical data suggests that the coefficient of renovation (volume of high water−volume of low water/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 current velocity during the flood tide at the Barra do Farol (main inlet southeast of Faro, Fig. 1) is shown in Table 1 together with other physical aspects of the lagoon. There is no evidence of stratification in the lagoon from these studies, as the relatively high currents mix thoroughly in the narrow and shallow channels.

Models are increasingly used for the management of lagoons and even a simple model, such as the Land Ocean Interactions in the Coastal Zone (LOICZ) nutrient budget, requires a good estimate of salinity and residence times (exchange rates) as essential information to calculate accurate salt budgets. Tett et al. (2003) have presented an exchange rate for the Ria Formosa based on the conservation of salt, according to the method of Officer (1976); they propose an exchange rate of 2.1 day^{-1} based on historical data which converts to 0.5 days when inverted to produce a residence time. Nonetheless, there are data suggesting that occurrences of poor water quality in this lagoon may be related to poor flushing (Newton and Mudge, 2003). This study investigates the hypothesis that a significant amount of the water in the lagoon is not exchanged with the north Atlantic and, while flushing is good in the outer parts of the lagoon, the inner reaches are poorly flushed. Salinity is used as a tracer for residence time as evaporative processes dominate over freshwater inputs in the summer months. Not only do the techniques used in this study provide more accurate data on salinity and residence times in the Ria Formosa, but they could also be useful for other similar coastal systems.

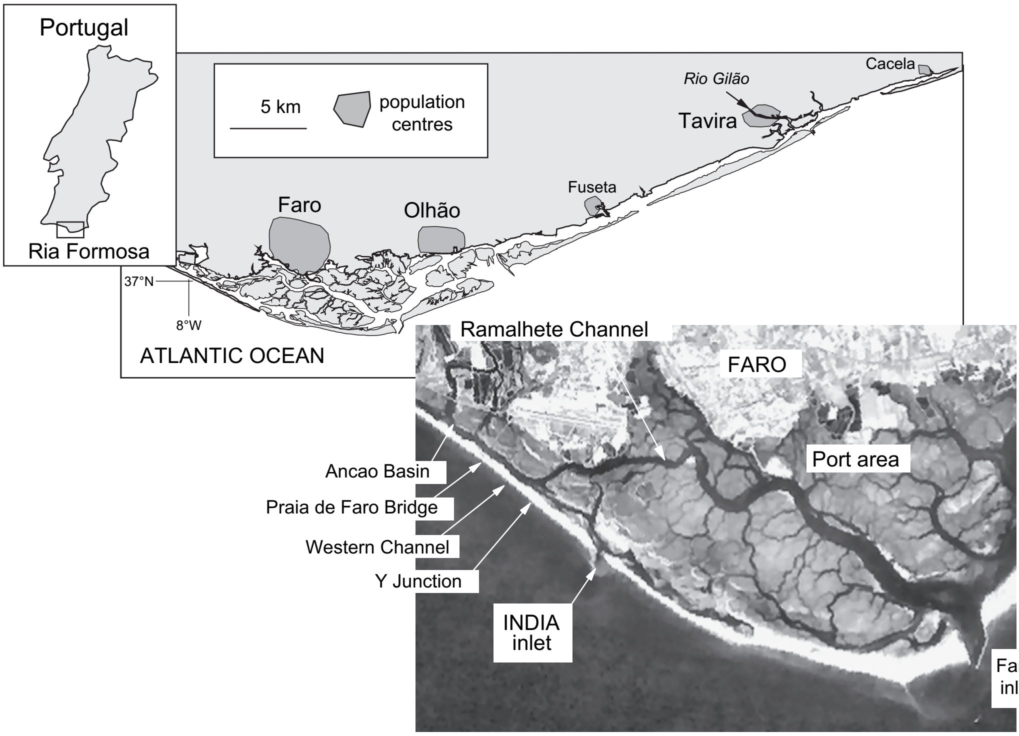

Fig. 1. Location of the Ria Formosa Lagoon, Portugal, including a more detailed image of the study area at the western end.

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Table 1
Maximum and minimum values for the salinity and temperature measured for the four states of the tide (LW = low water; MF = mid flood; HW = high water; ME = mid ebb) on both springs and neaps. Data for other physical parameters from $^{+}$Aguas, 1986; *Newton, 1995; $^{\#}$Lencart-Silva, 2001; ^{x}Lima and Vale, 1980.

		Spring tide				Neap tide			
		LW	MF	HW	ME	LW	MF	HW	ME
Salinity	Minimum	36.25	35.83	35.61	35.55	35.27	35.87	35.35	35.48
	Maximum	37.25	37.36	36.87	37.82	37.16	37.19	36.88	37.77
T (°C)	Minimum	22.60	21.55	21.51	23.97	23.51	21.17	20.46	22.19
	Maximum	25.17	26.46	26.27	28.44	28.73	24.75	24.56	28.05
Area submerged (km^2)$^{+}$		14.1		63.1		22.3		54	
Tidal volume ($\times 10^6$ m^3)*		32.6		139.3		46.4		92.6	
Flow velocity (m s^{-1})			1.3$^{\#}$		1.1$^{\#}$		0.4–0.5^{x}		0.4–0.8^{x}

2. Materials and methods

2.1. Temperature and salinity

Surveys of temperature and salinity were made of the western portion of the lagoon (Fig. 1) using a Seabird SBE-19 CTD mounted underneath a small boat. Measurements were recorded every 0.5 s to the internal memory and downloaded to a computer after each run. The data were processed using the Seabird Data Processing module (version 5.31a). Locations were recorded using a Garmin GPS-48 set to store the Universal Transversal Mercator (UTM) coordinates with the WGS84 datum every 15 s. These data were also downloaded after each run and the location interpolated between sampling times. The Universal Time Coordinated (UTC) record of time was used to match the two datasets together. Each series of measurements was centred about high water, low water, etc., and, depending on tidal flow, was completed within 60–80 min which represents ~10% of the tidal period.

Full temperature and salinity surveys from Farol to the Praia de Faro Bridge were conducted at high water, mid ebb, low water and mid flood for both spring and neap tides during June, 2004. Surveys of the junction between the Ramalhete Channel and Western Channel were made every hour over a 12 h period also in June, 2004. Over the experimental period and for two weeks either side, there was no rainfall in the lagoon or within the catchment.

2.2. Evaporation rate

The evaporation rate was determined from an experiment in a commercial salt pond within the Ria Formosa lagoon approximately 5 km from Faro. The salt pond had a surface area of 580 m^2 and an initial depth of 336 mm. Changes in salinity and water depth were measured over a 7 day period and the evaporation rate (mm day^{-1}) determined from both measurements. Water temperature within the pond increased over this period, but the mean value of 30 °C was close to that of the lagoon. The mean evaporation rate was converted to a proportion of the water column on the basis of the different depths found in the lagoon.

2.3. Calculation of residence time

Calculation of the residence time was based on box model work by Hearn and Robson (2002). In a simple system, the change in salinity in a trapped body of water was due to freshwater influx, evaporative losses and mixing with adjacent waters. This change became zero in lagoons, such as the Ria Formosa in summer, where there was no freshwater inflow. Therefore, increases in salinity above that of the inflowing seawater were due to evaporation of surface water and the length of time the water was in the system. It was now possible to calculate residence times from the following equation.

$$\text{Residence time (days)} = \frac{\Delta S}{S_{\text{i}} \times E}$$

ΔS is the difference in salinity between the inlet (S_{i}) and the measured salinity at any point, and E is the proportion of the water column evaporated per day.

The inlet salinity was averaged across several hundred values at high water on different days (when constant readings had been reached) and a value of 36.069 was used in the subsequent calculations.

3. Results

3.1. Farol to Praia de Faro series

The mean evaporation rate for the salt pond was 5.4 mm day^{-1} which compared well with a mean rate of 4.6 mm day^{-1} for a Brazilian lagoon during their summer months in January and February (Kjerfve et al., 1996). Using depth data for the inner lagoon, this rate was converted to a proportion of the water column. The calculated value used in the following calculations was 0.0065 which was larger than the suggested value of 0.001 (Hearn, personal communication). However, this was a shallow area which increased the proportion of the water column lost per day; if the waters had been deeper as in other estuarine examples, a lower value approaching 0.001 would have been obtained. The water depth of this shallow lagoon was predominantly less than 5 m and much of it is less than 1 m at high water.

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Each survey from Farol to the Praia de Faro Bridge (Fig. 1) yielded approximately 10,000–12,000 pairs of temperature and salinity which was equivalent to a sample measurement every 1.5–2 m. The range of values for each measurement is summarized in Table 1. Examples of the spatial distribution of salinity measured through the tidal cycle are shown in Fig. 2. These data are presented as a classed posting superimposed on a LandSat 7 image. At low water, the salinity of all water in this part of the lagoon was greater than the seawater outside the lagoon. The temperature was also significantly warmer (23–25 °C) than the Atlantic Ocean water (~20 °C, diagrams not shown); this feature could also be used to calculate the residence time, although this method was not used here. The tide transferred new seawater at a lower salinity than the outflowing water, demonstrating the reverse behaviour of this system in summer. At high water, the penetration of this new seawater can be seen in Fig. 2 by the distribution of the low salinity (36) water up the main channel to the port district. Evidence of some mixing was observed by the intermediate salinity water between this new seawater and the higher salinity lagoon water that was present at low water throughout the system. This high salinity water (37) was now confined to a section of the Ramalhete Channel near the Y-junction but still retained the characteristics it had at low water.

At the Y-junction, there was a distinct boundary between the high temperature and salinity water in the Ramalhete Channel and the low temperature and salinity water in the Western Channel between the INDIA (Inlet Dynamics Initiative: Algarve) inlet and the Ancão Basin. There was also evidence of mixing between the new seawater entering through the Western Channel and the water that was exiting from the Ancão Basin. The extent of the mixing could be seen at mid ebb where the intermediate salinity water occurred as a plug in the channels. There was also higher salinity water near the INDIA inlet containing water that was likely to have drained off the upper salt marsh regions; this water was not present in the neap tide survey data.

3.2. Residence time

The residence time was calculated from the salinity difference measured between the inlet and the other locations. These values might be considered to be the minimum times, as the evaporation rate, as a proportion of the water depth, was substantially greater than that suggested elsewhere. The derived times can be seen in Fig. 3 for high water and low water on both spring and neap tides in June, 2004. The data were coded according to their residence time with a non-linear scale. The first four categories covered a 24 h period and indicated the water that had entered the lagoon on the last two tides.

There was little difference between the low water patterns showing that the water in the channels had a mean residence time (±1 SD) of 2.4 ± 0.7 days on the spring tide and 2.1 ± 0.6 days on the neap tide. The values were almost homogeneous throughout the system at low water except for the extremities; slightly lower values were seen at the inlets and slightly higher values at the Ancão Bridge. At high water,

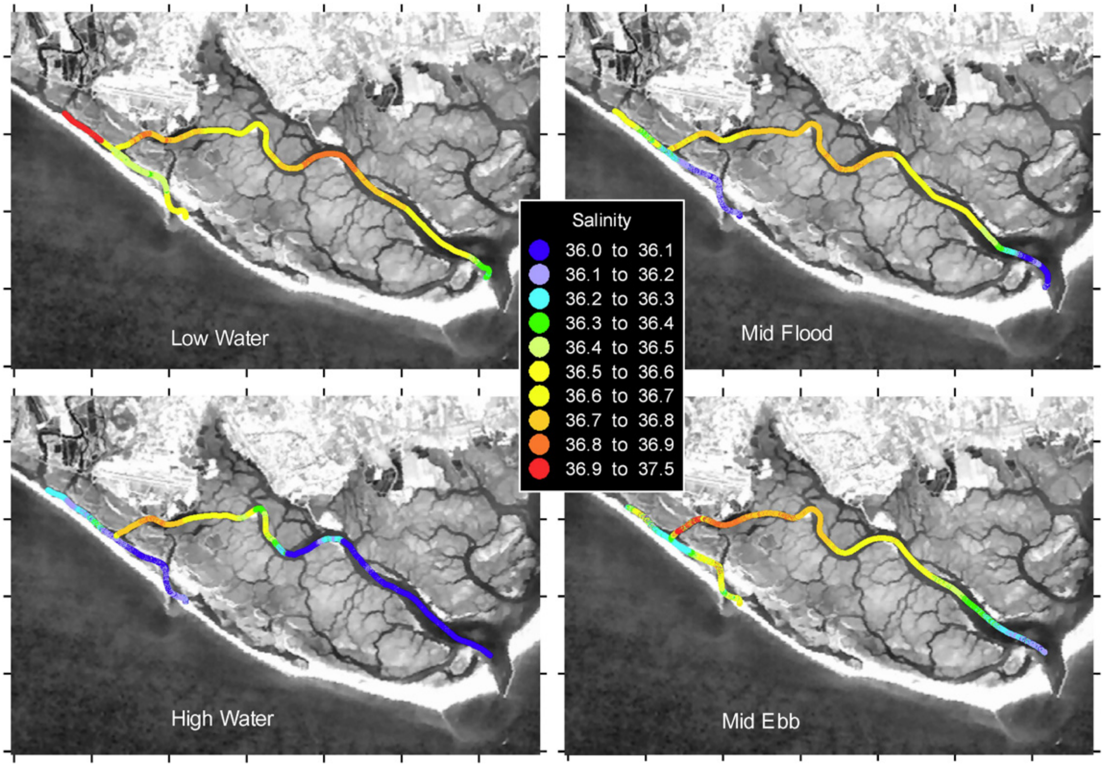

Fig. 2. Salinity at four states of a spring tide in June 2004 along the principle channels at the western end of the lagoon. The inset relates colour to the bands of salinity that were recorded along the channels; the mean value of the incoming north Atlantic water was 36.069.

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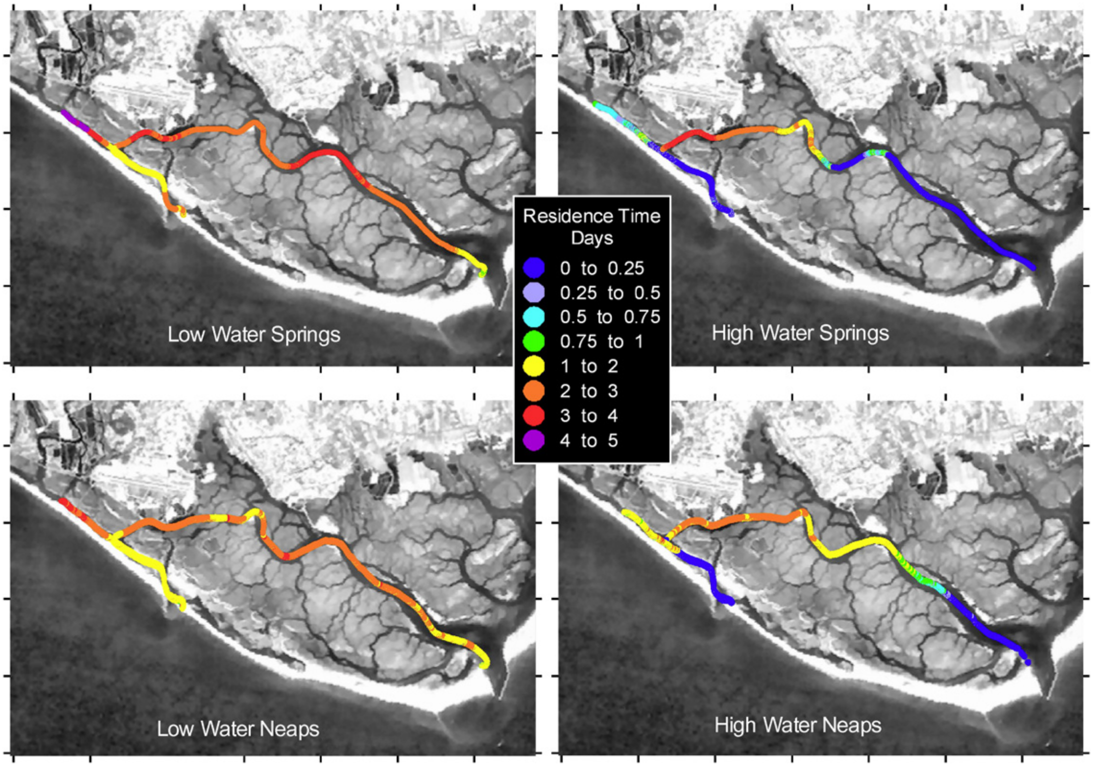

Fig. 3. Residence time in days for a spring and a neap tide in June at both low and high water. The inset relates colour to the bands of residence time that were calculated for the principle channels at the western end of the lagoon.

there was a more substantial difference between the tides with greater penetration of the new seawater up the channels on the spring tide. On the spring tide, the new seawater reached beyond the port region but not as far as Faro. On the neap tide, the new seawater only reached part way up the shipping channel towards Faro with little mixing of the inner waters with this new, less saline seawater. This was consistent with the authors' previously unpublished observations using a series of Lagrangian drifters in this channel; mean velocities of 0.5 m s^{-1} were measured and the drifters did not reach the port.

At high water on both tides, there was a substantial component of the water in the lagoon which had a residence time in excess of three days. This water did not readily mix either with the new seawater either in the Farol channel or at the other end with water from the INDIA inlet.

3.3. Y-junction series

The results of the calculations for residence time at the Y-junction, where the waters from the Ramalhete Channel (pushed up by incoming seawater at Farol) met in the Western Channel with the new seawater entering from the INDIA inlet, can be seen in Fig. 4. Although 12 surveys were completed, only four are shown (low water, midflood, high water and mid-ebb). At low water, the water in the channels had a residence time of 2–3 days with slightly lower values in the channel towards the INDIA inlet. At midflood, the new seawater was observed mixing with lagoon water of a longer residence time backed up in the Ramalhete Channel. Above the junction, intermediate values were observed from this mixing. At high water, the boundary between the two water masses was even more distinct with no evidence of any water from the INDIA inlet entering the Ramalhete Channel. The boundary between these water masses was in the order of 10–20 m at the junction.

As the water ebbed from the Ancão Basin, the mixed waters with an intermediate residence time could be seen leaving the lagoon by both the Western Channel towards the INDIA inlet and down the Ramalhete Channel towards Farol. The full survey data showed that this water did not clear the lagoon on a single tide and would be advected back up this channel on subsequent tides.

4. Discussion

Most of the waters of the Ria Formosa lagoon are well mixed with a rapid water exchange (Tett et al., 2003). The calculated coefficient of renovation based on the volume of water renewed each tide might also suggest this. However, earlier work by Newton and Mudge (2003) proposes a trapped body of water that is not well mixed and oscillates along the Ramalhete Channel and into the Ancão Basin. These new results confirm this hypothesis and show a hypersaline region in the upper reaches of the channels. This water becomes more saline with time, implying that the rate of evaporation exceeds the influx of freshwater to the lagoon, This influx is small over the summer period as there are no continually flowing rivers in

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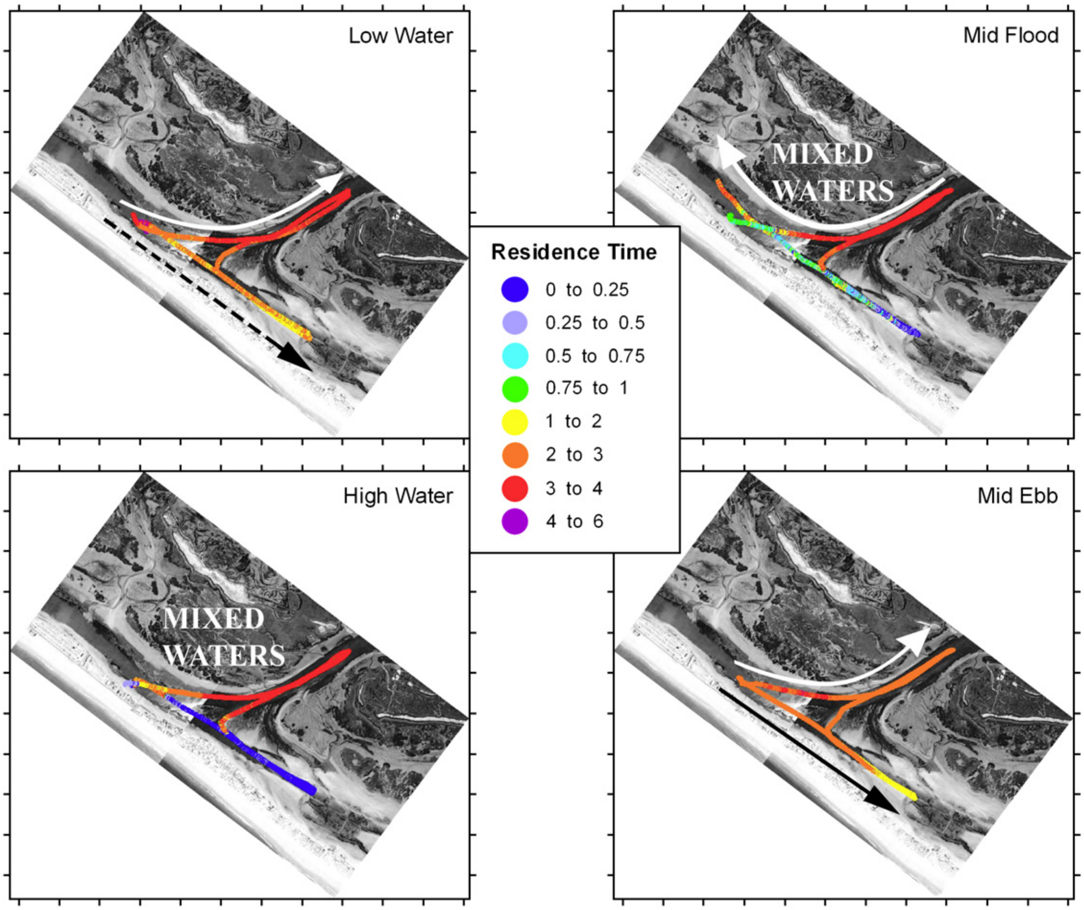

Fig. 4. Residence time in days at four states of a spring tide at the Y-junction boundary between the Ramalhete Channel and the Western Channel. The inset relates colour to the bands of calculated residence time along the channels of the Y-junction. The movements of water bodies associated with the Ramalhete (inner lagoon) and the Western (outer lagoon) Channels are shown with white and black arrows, respectively.

this section of the lagoon, and rainfall is generally confined to the winter months.

The salinity of this trapped water at this time of year is up to 1.5 greater than the incoming seawater. Greater values (3.0) have also been measured in this system later in the year (Newton and Mudge, 2003), which would correspond to a residence time of ~12 days. Presumably, the slow mixing with incoming seawater will limit the maximum residence time. The supposition that the waters of this lagoon are rapidly exchanged and the system is flushed clean is probably true for the outer channels (Nobre et al., 2005), but it is not the case for the water in the inner reaches of the system.

This reduction in water exchange has implications, not only for modelling the Ria Formasa, but also for management. The principle sewage discharge for the urban area of Faro is into the Ramalhete Channel where the relatively long residence time will increase both biological oxygen demand and the fluctuation in oxygen levels, with both super- and under-saturation during day and night time, respectively. There is also enhanced deposition of particulate matter in the Ramalhete Channel along the fork of the Y-junction (Mudge and Duce, 2005), which is due to the water from the INDIA inlet reducing the penetration of the water backed up from Farol.

Some of the effects of reduced exchange on the discharged organic waste could be considered positive. The waters are exposed to high ultraviolet light during their passage from the pipe to the designated bathing beaches which are located on the outside of the barrier islands and sand spits; this reduces the number of viable bacteria so these beaches meet both the European Union mandatory and guideline standards for bathing water quality (76/160/EEC). The sediments of the inner lagoon are also used extensively for shellfish culture and the high organic matter retained in the system may be acting as a food source for this aquaculture.

Nonetheless, there are probable negative effects. There are increased mortalities of shellfish in recent years, particularly, in the inner lagoon which may be the result of a reduction in water quality (Associação dos Marisqueiros, personal communication). Also, the increased deposition of particulate organic matter in one of the principle channels will necessitate dredging, both for navigation and water circulation.

5. Conclusions

1. The detailed salinity and temperature structure in the present study showed that the residence time had been

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underestimated for the inner regions of the Ria Formosa lagoon. This data should be taken into account for the future management of the Ria Formosa as well as providing essential information for the application of models such as the LOICZ nutrient box model.

2. The techniques for estimating residence time in this study could be a rapid and cost effective approach to testing assumptions about water exchange in other shallow coastal systems.

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