

# Impact of Coastal Engineering on the Water Quality of the Ria Formosa Lagoon, Portugal

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## Abstract

The Ria Formosa is a coastal lagoon in southern Portugal. It is a Ramsar and Natura 2000 site and supports important resources such as fisheries, aquaculture and tourism. Human impacts on the Ria Formosa include urbanization, intensive agriculture, aquaculture, and coastal engineering.

In this rare, long-term study of a coastal lagoon, the effects of changes in coastal zone management are documented. Data from studies over 12 years are compared to follow the impact of coastal engineering on the water quality of the lagoon.

The studies are:

- Prior to the opening of the INDIA inlet
- Following the opening of the inlet (prior to the operation of the sewage treatment plant)
- After the start of the sewage treatment plant operation

Recent modifications to the lagoon appear to have improved the water quality of the western lagoon with respect to dissolved oxygen percentage saturation.

## 1. INTRODUCTION

The Ria Formosa is a shallow mesotidal lagoon on the south coast of Portugal, (Fig. 1). This Ramsar site is also part of the NATURA 2000 network, and supports important natural resources such as fisheries, aquaculture and tourism. Human impacts on the Ria Formosa include urbanization, intensive agriculture, aquaculture, as well as coastal engineering such as artificial inlets.

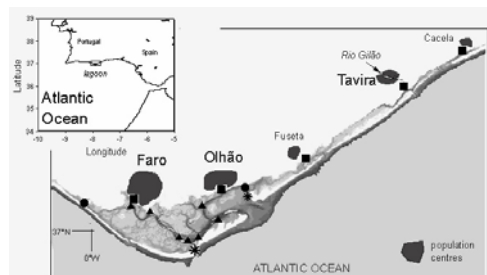


Figure 1: Location of the Ria Formosa Lagoon. The range of conditions is represented by a different symbols: ●, landward boundary conditions; ж, seaward boundary conditions; ▲, intermediate lagoon conditions; ■, exposure to domestic sewage and/or freshwater.

It is not clear whether coastal (tidal) lagoons such as the Ria Formosa will be considered as “Transitional” or “Coastal” waters, according to Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (E.U., 2000). The Ria Formosa re-

ceives inputs from small rivers (Gilão, Almargin) and seasonal streams and exchanges water tidally with the Atlantic Ocean through 6 inlets (Barras) and, as such, could be considered to be “transitional”. However, 90% of the volume of the lagoon is exchanged with each tide, so it may also be considered as “coastal” water. It is the water quality of the inner areas of the lagoon that is most likely to be compromised, (Newton 1995). There is little industry around the lagoon but the area is heavily urbanized. The hydrographic basin of the Ria Formosa also includes areas subjected to intensive agriculture and animal rearing (poultry and pigs) so that the lagoon is at risk of eutrophication, (Newton *et al* 2001).

According to the Water Framework Directive, (E.U. 2000), a “heavily modified water body” means a body of surface water which as a result of physical alterations by human activity is substantially changed in character. Coastal engineering and infrastructure in the western part of the Ria Formosa includes the main inlet at Barra do Farol, the construction of dykes retaining freshwaters from the Ribeira de São Lourenço stream, the formation of artificial freshwater lakes, the artificial inlet opening of the INDIA project in 1997, the construction of an international airport on the mudflats and two large sewage treatment plants to the East and West of Faro town that came into operation in 2000. The western end of the lagoon was also dredged recently in 2000. It is therefore arguable whether the western end of the Ria Formosa is a “heavily modified water body”.

Eutrophication is defined by the European Environment Agency as “an increase in the rate of supply of organic matter to an ecosystem, which most commonly is related to nutrient enrichment enhancing the primary production in the system” (EEA 2001).

A survey of the USA estuaries found that 70% were affected to some degree by eutrophication (Bricker *et al* 1999, NRC 2000). Problems are particularly severe along the mid-Atlantic coast, Chesapeake Bay and the Gulf of Mexico, where a “dead zone” forms along the Louisiana and Texas coasts each spring, (Turner and Rabalais 1994). This “dead zone” is characterised by hypoxia, low dissolved oxygen concentrations (Rabalais *et al* 1991).

The solubility of oxygen in seawater is partially controlled by temperature and salinity. Oxygen is less soluble in warm saline waters than in cold fresh waters. Furthermore, microbial activity (and consequent oxygen utilization by heterotrophs), is greater in warm than cold conditions. The temperature and salinities of the western part Ria Formosa in the summer months (June-September) are warm (~24°C) and hypersaline (36-39), (Newton and Mudge in press), nevertheless low dissolved oxygen concentrations (or percentage saturation) are not often observed. The water is frequently supersaturated with respect to oxygen, (Newton *et al* in press).

Dissolved oxygen percentage saturation during daily and diurnal tidal cycles are presented in this paper with and discussed with respect to the “modifications” in the western part of the Ria Formosa.

## 2. METHODS

### 2.1 Description of the sampling station:

The sampling station was selected because it integrated various aspects of coastal zone management: it is important for bathing, shellfish aquaculture and tourism.

The exact location of the sampling station is at the base of the steps, half way across the bridge giving access to Faro beach, “Praia de Faro”. The beach is a narrow, approximately 50m wide, peninsula of sand dunes separating the lagoon from the ocean. The sampling station is at 3 km from the closest inlet, Barra de INDIA, and at 6 km from the town of Faro.

Down from the sampling station, at a distance of 2 km, the channel forks: one channel leads to the inlet at Barra da INDIA and the other channel flows inland towards the town of Faro and joins up with the main Faro channel. The channel ends 5 km to the west of the sampling station. One kilometer to the west is the stream “Ribeira de São Lourenço”.

The channel at the sampling station is narrow (approximately 60m wide) and very shallow at low water, (less than 2m deep). At high water,

however, the channel is approximately 1 km wide. The pillars supporting the bridge are set close together, 2m between pillars, and these cause considerable turbulence and mixing during the ebb and flood of the tide.

To the north of the sampling station, large expanses of mud-flats and salt-marsh are exposed at low water from which clams, cockles and fiddler crabs are collected. Slightly to the west there is a large area of salt-extraction pans associated with the Ribeira de São Lourenço system. Some of the salt-pans have recently been converted to extensive aquaculture. To the west of the Ribeira de São Lourenço system, there is an area of intensive farming that is surrounded by a pine forest. The municipal dump is also situated here. An International airport is adjacent to the sampling station, to the north-east. At the east end of the lagoon, there is a large tourist development, Quinta do Lago, that includes an artificial lake. To the south of the sampling station, across the bridge, the sand-dune peninsula has been urbanised. During the summer months, this is an important tourist resort and recreational area for the inhabitants of Faro and seasonal visitors.

### 2.2 Sampling dates:

The sampling took place in the summer months (June to September) on three separate occasions, 1989, 1997 and 2000. These represent three stages in the “modification” of the lagoon:

- prior to the opening of the INDIA inlet;
- after the opening of the INDIA inlet but prior to the operation of the sewage plant (ETAR de Montenegro);
- after the start of the sewage plant operation and dredging.

The date, times and state of the tide of tide of the sampling events are given in Table 1.

Table 1: Date, times and state of tide of sampling events. H.W.= High Water, L.W.= Low Water

Date	29-09-1989	17&18-09-1997	30-06-2000
Start	0900	1616	0030
End	2130		2130
HW		1616	0100
LW	0930	2320	0800
HW	1530	0450	1430
LW	2130	1150	2100
HW		1650	

The times of Low and High water correspond to observed “slack” water rather than the tide tables, as there is a delay between the time of the tide at the inlet and at the sampling station.

### 2.3 Field and laboratory procedures:

Field measurements of temperature and salinity were taken in the surface meter of water using a temperature and salinity bridge (S.T. Bridge MC5, Electronic Switchgear London Ltd, Nat. Inst. Ocean). The calibration was checked in the laboratory before field-work using a laboratory thermometer and standard seawater. Water samples were taken from the first metre of water below the surface using a Nansen-type bottle. All the samples collected were processed by the procedure detailed below.

Numbered glass bottles, of known volume, fitted with numbered glass stoppers were used for the dissolved oxygen samples. The bottles were the first to be filled from the outflow tube of the water sampler. The bottle was flushed, taking care to insert the tube to the bottom of the bottle. The flow was controlled so that the bottle filled rapidly but without turbulence or bubbling. Once overflowing, the tube was slowly withdrawn from the bottle. 1 cm<sup>3</sup> of manganese (II) chloride reagent and 1 cm<sup>3</sup> of the alkaline iodide reagent were added to the samples with automatic volume dispensers. The glass bottle was closed carefully, avoiding trapping any air bubbles, and then shaken. The sample bottles were transported, upside down and in the dark, in a screw-top jar containing water. The samples were analysed as soon as possible on return to the laboratory by the Winkler method (Grasshoff *et al* 1983).

## 3. RESULTS AND DISCUSSION

### 3.1 Dissolved oxygen percentage saturation prior to the opening of the INDIA inlet

On the 29th of September, the greatest spring tide of the year, low water tidal height was 0.8m and high water tidal height was 3.4m, giving a tidal range of 2.6m. The observations recorded on the 29-09-1989 are shown in Figure 2.

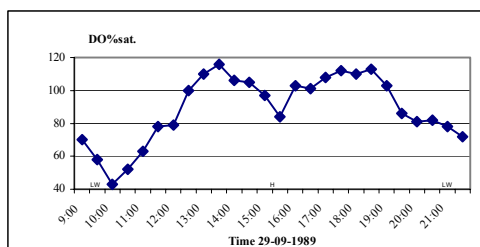


Figure 2: Variation in Observed Dissolved Oxygen Percentage Saturation on 29-09-1989

The oxygen minimum (43%, 3.9 mg.dm<sup>-3</sup>) was recorded at 10:00, shortly after low water. The combined effects of consumption of oxygen during the previous night, low rates of reaeration at slack water, and contact with organic rich or re-

ducing sediments in shallow channels may have contributed to the minimum observed at 10:00.

As the tide flooded during the morning, the oxygen levels increased to 116%, 8.2 mg dm<sup>-3</sup> by 12:45. The increase in oxygen also results from the combined effect of several factors. The water brought past the sampling by the tide came from the outer lagoon and the ocean and would not have been subjected to the reducing effect of the anoxic sediments in the shallower parts of the inner lagoon. Reaeration increases with current speed and will raise the dissolved oxygen percentage saturation to 100%. Supersaturation results from the photosynthetic production of oxygen that increases during the daylight hours.

At 14:30, shortly before high water, the dissolved oxygen percentage saturation decreased to 105%. This was concurrent with troughs in salinity and temperature. These features identified the tidal flood.

The decline in oxygen levels continued and become more abrupt reaching 78% at 15:30. This further decrease in oxygen, in contrast, was concurrent with peaks in the temperature and salinity observations. This water had probably been in the shallow channels of the saltmarsh, close to a sewage outlet to the East, and was then flushed past the sampling station by the flooding tide. This would explain the nutrient loading, high temperature and salinity as well as the low oxygen observed in this 'tidal pulse'. The data indicate that this patch of water had passed the sampling station by 15:45.

The water flowing past the sampling station on the ebb would have been in the shallow channels in the western inner lagoon where photosynthetic oxygen production resulted in some supersaturation, 109% by 16:15. At 16:30, there was a small oxygen trough concurrent with high salinity, temperature. After sunset at 19:00, the oxygen levels dropped rapidly as photosynthetic production ceased and consumption continued.

### 3.2 Dissolved oxygen percentage saturation after the opening of the INDIA inlet but prior to the operation of the sewage plant (ETAR de Montenegro)

The observations recorded on the 17<sup>th</sup> and 18<sup>th</sup> - 09-1989, the biggest tide of the year, are shown in Figure 3.

Sampling started at High Water in the afternoon of the 17<sup>th</sup> of September 1987. The water was supersaturated with respect to oxygen (>120%) due to high rates of primary productivity. The dissolved oxygen percentage saturation decreased during the evening ebb until 20:20. From 20:50 to 23:50 (just after low water, a patch of nearly saturated water (95-100%) flowed past the sampling station. The dissolved oxygen percentage saturation then continued to decrease until 00:30, reaching a minimum of 67%.

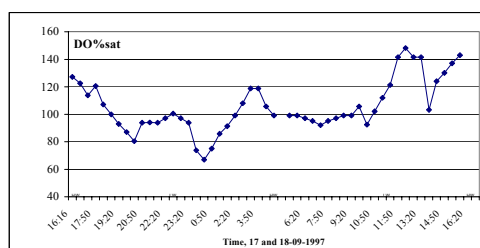


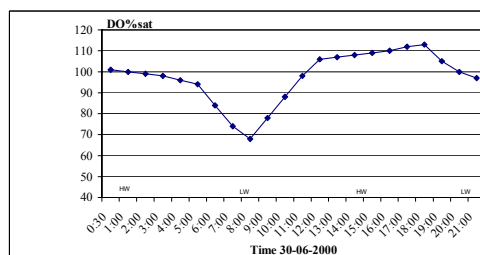
Figure 3: Variation in Observed Dissolved Oxygen Percentage Saturation on the 17th and 18th -09-1989.

The dissolved oxygen percentage saturation increased during the flood until 04:20 as well oxygenated water flowed into the lagoon from the inlet. However, after high water there was a decrease in the dissolved oxygen percentage saturation until 10:20, just before low water. The dissolved oxygen percentage saturation increased rapidly during the afternoon flood, reaching a very high maximum of 148% at 12:20. A sharp trough was observed at 13:50, during the afternoon ebb.

### 3.3 Dissolved oxygen percentage saturation after the start of the sewage plant operation (ETAR de Montenegro) and dredging.

The observations recorded on the 30-06-2000 are shown in Figure 4.

Figure 4: Variation in Observed Dissolved Oxygen



Percentage Saturation on the 30-06-2000.

Sampling started at high water in the middle of the night 00:30. There was a night-time decrease in the dissolved oxygen percentage saturation that continued through the early morning ebb, reaching a minimum of 68% by Low water at 0800. The dissolved oxygen percentage saturation increased during the daytime flood and ebb reaching 113% at 1900. At dusk the dissolved oxygen percentage saturation started to decrease reaching 97% by 21:00.

### 3.4 Comparison of the results obtained in the different studies

Table 2 compares the results obtained in the three studies. The night-time minima in dissolved oxygen percentage saturation are not very severe in any of the documented situation, and the situation seems to have improved following the opening of the INDIA inlet. There is no signifi-

cant difference between the minima registered prior and post the opening of the sewage treatment plant and the dredging.

Table 2: number of hours of sampling, the dissolved oxygen percentage saturation maxima and minima recorded on each sampling occasion as well as the number of peaks and troughs recorded.

Date	29-09-1989	17&18-09-1997	30-06-2000
Sampling hours	13	24	21
min.D.O% sat.	43	67	68
max.D.O% sat.	116	148	113
Number of peaks	2	3	1
Number of troughs	2	4	1

The maximum recorded in 1997 was very high (148%). This indicates the potential for very high photosynthetic primary production in this nutrient rich lagoon exposed to high light intensities.

## 4. CONCLUSIONS

Even allowing for the different number of sampling hours, it is possible to see that the observations made after the opening of the sewage treatment plant and the dredging are less "spiky". This is due to better circulation in the inner channels of the western lagoon. Prior to this, the shallowness of the lagoon restricted circulation and this resulted in "patchiness" of the water flowing past the sampling station during both the flood and the ebb, as small creeks and pools overflowed and then drained into the tidal waters. In comparison, the effect of the opening of the INDIA inlet is of little importance, confirming that water exchange at the Barra do Farol still influences the western lagoon.

"Modifications" in the western part of the Ria Formosa have had a pronounced effect on the dissolved oxygen percentage saturation of the Ria Formosa lagoon. The water quality of the western Ria Formosa improved significantly as a result of the opening of the "INDIA" inlet. Dredging and the installation of a sewage treatment plant, the ETAR of Montenegro have also contributed to better dissolved oxygen percentage saturation within the lagoon.

Although the Water Framework Directive refers to "heavily modified water body", this is as yet not well defined. In the case of the Ria Formosa, recent modifications appear to have improved the water quality of the western lagoon with respect to dissolved oxygen percentage saturation.

This is a rare example of a long-term study of a coastal system where the effects of changes in coastal zone management have been documented.

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