Marine Pollution Bulletin xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Determining the footprint of sewage discharges in a coastal lagoon in South-Western Europe

Alexandra Cravo [a,*], Denise Fernandes [a], Tânia Damião [a], Catarina Pereira [b], Margarida P. Reis [a]

[a] University of Algarve, FCT – CIMA, Campus de Gambelas, 8005-139 Faro, Portugal
[b] CCMAR, University of Algarve, Campus of Gambelas, 8005-139 Faro, Portugal

ARTICLE INFO

Article history:
Received 16 February 2015
Revised 9 May 2015
Accepted 12 May 2015
Available online xxxx

Keywords:
Sewage discharges
Ria Formosa
Nutrients
Faecal coliforms
Eutrophication
TRIX index

ABSTRACT

Ria Formosa is a highly productive lagoon in South-Western Europe, supporting 90% of Portuguese clam production. Decreases in shellfish production have been ascribed to deterioration of water quality due to sewage discharges. Nevertheless, a thorough study considering their impact on the whole lagoon system has been missing. This work determined the sewage footprint from the major sewage treatment plants (STP) regarding eutrophication and microbial contamination within a two-year monitoring program. This focused on salinity, oxygen, nutrients, chlorophyll-*a* and faecal coliforms. Areas closer to sewage discharges showed an evident impact with maximum effects detected at the major STP. However, globally, the Ria Formosa did not show clear eutrophication problems due to high tidal flushing. Ammonium, oxygen, chlorophyll-*a* and faecal coliforms, unlike the other parameters, showed no seasonality. Microbiological contamination was of great concern and public health issues could be avoided by settling shellfish beds at least 500 m away from discharge points.

1. Introduction

There are numerous cases in the literature showing the deleterious effects of sewage discharges on the water quality, including eutrophication of coastal zones (Cloern, 2001). Eutrophication in coastal lagoons of Europe has been reported in several case-studies (García-Pintado et al., 2007; Lloret et al., 2008; Roselli et al., 2009, 2013). Coastal lagoons under risk of eutrophication from impacts of sewage discharge impacts, require water quality assessment and preservation, as proposed by the OSPAR Eutrophication Strategy, so as to manage or avoid adverse effects such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen limitation (particularly in bottom waters) (OSPAR, 2009). However, sewage impacts are not limited to eutrophication but also include human health risks transmitted by microbiological contaminations either by direct/indirect contact with water (ingestion, aerosol/liquid inhalation, epidermal contact, etc.) or by consumption of edible resources, such as shellfish. In areas where edible resources are harvested, water quality protection and safeguarding are among the most important priorities, preferentially based on a suitable management strategy that takes into account sources of contamination and dispersal pathways.

Coastal lagoons are usually highly productive systems with ecological and economic importance to local and regional communities, and thus liable to the impacts of human activities. Such is the case of Ria Formosa, a highly productive coastal lagoon (Falcão and Vale, 1990; Newton et al., 2003; Mudge and Duce, 2005), located in South-Western Europe, along the south Portuguese coast. This large and shallow multi-inlet barrier island system has a total area of ~10,000 ha, that has a key ecological role by supporting migratory birds and serving as breeding and nursery area for many fish and mollusc species, with a noticeable economic impact in terms of benthic bivalve production (Newton et al., 2003).

The well-preserved natural conditions of the Ria Formosa led to its designation as a National Park in 1987 and inclusion in the Ramsar Convention and Natura 2000 European network. The lagoon is of high socio-economic importance to the region mainly due to tourism and shellfish related activities, which involve ca. 10,000 people. The bivalve harvesting area occupies ca. 500 ha with approximately 1500 shellfish beds and produces almost 90% of the clam production in Portugal (Serpa et al., 2005; DRPASul, 2006). However, from more than 7000 tons of *Ruditapes decussatus* in the 80s (Cachola, 1996), the annual harvest of this economically valuable species decreased severely in the late 90s, barely reaching

* Corresponding author.
E-mail address: acravo@ualg.pt (A. Cravo).

http://dx.doi.org/10.1016/j.marpolbul.2015.05.029
0025-326X/

Table 1
Characteristics of the main sewage treatment plants (STP) located at the Ria Formosa lagoon system and features of their respective area of effluent discharge. The sampling areas selected are: in the area of Faro city (FN and FNO), Olhão city (ON and OP) and Tavira city (Tavira), as indicated in Fig. 1.

STP	Treatment system	Maximum equivalent served population	Average flow (m^3/d)	Features of the area of effluent discharge
FN	Aerobic ponds	87,000	10,600	Narrow and shallow channel; at low water the western side is almost voided of seawater, i.e. is dry
FNO	Aerobic ponds	12,000	3600	Shallow channel, larger than FN; the wideness and depth increases rapidly with distance from the discharge point; at low water, the channel never dries
ON	Activated sludge and aerobic stabilization ponds	11,000	500	Main channel in front of Olhão city (Canal de Marim); one of the largest and deepest in Ria Formosa, connected with the Armona inlet
OP	Aerobic stabilization ponds	45,000	4000	Narrow and shallower channel, although larger and deeper than FN
Tavira	Aerobic stabilization ponds	30,000	5400	Estuary of Gilão river, in front of Tavira inlet; the largest and deepest channel of all

2500 tons in 2010 (DGPA, 2011). This corresponds to a clam production of 0.5 kg/m^2 instead of the previously estimated averages of 3–4 kg/m^2, up to 7 kg/m^2 (Cachola, 1996; Mudge and Bebianno, 1997). Water quality deterioration, attributed to the impact due to sewage discharge impacts, uncontrolled economic development and increasing anthropogenic pressures, have been held responsible for the decrease of shellfish production over recent decades (Bebianno, 1995; Mudge and Bebianno, 1997; Mudge et al., 1998, 1999; Newton et al., 2003). However, and despite several works devoted to water quality, no study has focused specifically on the global impact of discharges from sewage treatment plants (STP) on the Ria Formosa system.

STP for the main cities started to operate by the late 80s – early 90s and, even now, treated domestic sewage discharges (with small contributions from some industrial effluents) continue to represent one of the most important pressures upon water quality of this lagoon. The resident population of the principal cities (Faro, Olhão and Tavira) amounts to about 125,000 inhabitants (INE, 2012) with an estimated daily sewage discharge in the early 2000s of about 14,000 m^3, 4500 m^3 and 5500 m^3, respectively (Table 1). Demographic enhancement in the summer months due to tourism can easily reach a magnifying factor of 4–5 (Newton et al., 2014) with a significant increase of summer sewage discharges into the lagoon. However, their impacts depend upon the hydrodynamic conditions and regardless of that fact, an increasing concern regarding food safety has been raised particularly in mollusc shellfish products, namely clams (Oliveira et al., 2011).

According to national legislation, the Ria Formosa lagoon is considered as "shellfish waters" (DL 236/98 – Diário da República, 1998, transposing the European Shellfish Directive EEC, 1979), and as a sensitive area that must be protected against eutrophication (DL 149/2004; Diário da República, 2004, transposing the European Urban Wastewater Treatment Directive EEC, 1991a). Therefore, this valuable resource demands a better water quality assessment to understand its susceptibility to sewage contamination, particularly in the vicinity of shellfish bed areas. In this context, the present work represents the most comprehensive (spatial and temporal) study on the receiving waters close to the five major STP from the main cities of the Ria Formosa, and paid particular attention to shellfish beds and natural banks of bivalves. To assess the effects of multiple stressors driven by sewage discharges in the Ria Formosa coastal lagoon several questions were raised:

(a) Is the water quality impaired and if affirmative, which is the most indicative parameter?
(b) What is the extent of the impact within and among the five study areas?
(c) How does tidal flushing affect the water quality?
(d) How does seasonality affect the results?
(e) What are the eutrophication trends in the lagoon when applying the trophic index – TRIX (EEA, 2001)?

2. Material and methods

2.1. Study area description

The Ria Formosa (Fig. 1) is a mesotidal lagoon (semidiurnal tides, mean tidal range of ~2 m) with more than 90 km^2, separated from the sea by 6 inlets and with several channels and innumerable straits. It extends from 36°58′N, 8°2′W to 37°3′N, 7°32′W, for about 55 km (E–W) and is 6 km at its widest point. On a daily basis, the water exchange with the ocean accounts for 50–75% (Mudge et al., 2008) reaching values of $\sim 80 \times 106\ m^3$, $150 \times 106\ m^3$ and $\approx 115 \times 106\ m^3$ in neap, spring and intermediate tides, respectively (Neves et al., 1994). The Ria Formosa lagoon is a prevailing marine system, with a typical salinity value around 36 in the main channels. The exception is near Tavira, where the Gilão river discharges (Falcão and Vale, 1990; Newton and Mudge, 2003) and close to the several STP. The freshwater discharge from the effluents globally represents $\sim 2.5 \times 104\ m^3$/day, a much lower volume than the exchanged with the sea.

2.2. Sampling

Within the Ria Formosa lagoon system there are five major STP from the main cities *viz.* two in Faro (Faro Nascente – FN and Faro Noroeste – FNO), two in Olhão (Olhão Nascente – ON and Olhão Poente – OP) and one in Tavira (Fig. 1). Their main characteristics together, with the description of the sewage discharges area are listed in Table 1.

At each of the five STP areas (Fig. 1) several stations were selected, spaced at a minimum of 100–200 m from each other, over an area of 1–2 km from the sewage discharge point to reach as many shellfish beds or natural banks as possible. In the Tavira sampling area, water samples were also collected upstream of the sewage discharge point (~650 m) to evaluate the freshwater influence/contribution from the Gilão River (Fig. 1e). In addition, two reference stations were selected: one located at a main channel in Faro (FN ~2050 W; Fig. 1b) and another in front of Tavira's main inlet (~1600 m; Fig. 1e).

Surface water samples (20–30 cm depth) were collected on a monthly basis, in pre-cleaned polyethylene bottles, from May 2001 to December 2002 (23 sampling campaigns). Samples for microbiological determinations, from October 2001 to December 2002 (18 sampling campaigns), were taken in sterile Schott Duran glass bottles and kept in the dark in cold containers (<5 °C) for immediate analysis upon arrival at the laboratory (within 6 h). The sampling frequency was increased fortnightly during summer months (July to September) to account for an expected increase in anthropogenic pressure from the touristic influx. During each sampling campaign, to characterize the effect of tidal flushing, water samples were collected at opposite tidal conditions (twice a day, at both low and high water). At reference