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Dissolved oxygen in the rehabilitation phase of an estuary: Influence of sewage pollution abatement and hydro-climatic factors

Fernando Villate [a,*], Arantza Iriarte [a], Ibon Uriarte [a], Lander Intxausti [b], Alejandro de la Sota [c]

[a] Department of Plant Biology and Ecology, University of the Basque Country, 48080 Bilbao, Spain
[b] Department of Didactics of Science, EUMBAM, Barrainkua 2, 48009 Bilbao, Spain
[c] Bilbao Bizkaia Water Consortium, EDAR de Galindo, Maisu Jose s/n, 48910 Bilbao, Spain

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ABSTRACT

Seasonal and inter-annual variations of dissolved oxygen (DO) along the estuary of Bilbao were investigated from 1998 to 2008, during its rehabilitation phase from pollution, to determine whether anthropogenic or natural forcings or both govern DO dynamics and hypoxia. Both seasonal and inter-annual variations of DO were best explained by hydro-climatic factors, sewage pollution and phytoplankton dynamics in the inner, intermediate and outer estuary respectively. The most remarkable intra-decadal improvement in DO occurred in the halocline layer of the intermediate estuary, where the factor that best explained these changes was sewage pollution abatement. However, in the estuarine hotspot for hypoxia, i.e. inner estuary bottom waters, no parallel response to sewage pollution abatement was observed and hydro-climatic factors were the main drivers of inter-annual DO variations. Differences in the degree of stratification and flushing accounted for this differential response of DO to anthropogenic and climate-related forcings at both axial and vertical scales.

1. Introduction

Hypoxic conditions (<2 mg l^{-1}, or approximately 30% saturation, see Rabalais et al., 2010) reduce the extent and suitability of habitat for a wide range of organisms (Breitburg et al., 2003; Diaz and Rosenberg, 2008) and can cause multiple adverse effects from the individual to the ecosystem level, including organism mortality, reduced population densities, loss of biodiversity, changes in trophic structure and alteration of ecosystem functions and services (see Rabalais et al., 2002); hence, trends in dissolved oxygen (DO) and their driving factors constitute a central topic in aquatic ecology. In estuaries DO variations can be affected by a combination of an array of both natural and anthropogenic factors. Excessive organic production due to hypernutrification (i.e. eutrophication), direct organic enrichment, water column stratification and low flushing time favour DO depletion (Kemp et al., 2009; Welsh and Eller, 1991; Wiseman et al., 1997); whereas wind and tides induced water column mixing can prevent the development of hypoxia (Hagy and Murrell, 2007; Lin et al., 2008). Warming can promote opposite effects depending on other factors since it may enhance both oxygen consumption rates (Kemp et al., 1992; Sampou and Kemp, 1994), and autotrophic oxygen production rates (Davison, 1991), and it may also decrease oxygen solubility. This underscores the fact that, in addition to the effect of organic and nutrient enrichment, the potential effect of global climate change should be taken into account when analyzing DO trends. Also, in estuarine systems, due to their heterogeneity (physiography, hydrodynamics, anthropogenic activities), the relative importance of each of these factors can vary from estuary to estuary and even from site to site within each estuary (Codiga et al., 2009; Iriarte et al., 2010), as well as on different time-scales (Rabalais et al., 2010).

Overall, DO levels have been shown to be declining in the marine environment, both in the open ocean and in coastal and estuarine areas (Keeling and García, 2002; Diaz and Rosenberg, 2008; Gilbert et al., 2010; Li et al., 2011). Cultural eutrophication has been claimed to be the major process responsible for the long-term increase in hypoxia and anoxia in coastal and estuarine areas around the world (Diaz, 2001). In the last decades, though, management plans conducive to reductions in organic and nutrient enrichments have been implemented in some estuarine and coastal systems, and it is only relatively recently that the scientific community has started to make comparative analyses of the observed trajectories of hypoxia response in different estuarine and coastal systems (Duarte et al., 2009; Kemp et al., 2009; Borja et al., 2010; Rabalais et al., 2010).

In the 20th century, the estuary of Bilbao, located on the Basque coast (Bay of Biscay), became a highly polluted estuary that received large amounts of untreated domestic sewage and industrial

* Corresponding author. Address: University of the Basque Country, Faculty of Science and Technology, Department of Plant Biology and Ecology, PO Box 644, 48080 Bilbao, Spain. Tel.: +34 94 601 55 15; fax: +34 94 601 35 00.
E-mail address: fernando.villate@ehu.es (F. Villate).

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wastes. Extensive areas of the estuary developed hypoxia (Iriarte et al., 1998; Borja et al., 2006) and inner areas of the estuary became anoxic and practically devoid of fauna (González-Oreja and Sáiz-Salinas, 1998; Uriarte and Borja, 2009). The progressive implementation of a sewage treatment plan for the metropolitan area of Bilbao since the 1980s has been claimed to be responsible for an overall improvement in oxygen levels in the estuary (García-Barcina et al., 2006; Borja et al., 2010). However, the analysis of the factors responsible for the inter-annual changes in DO in the rehabilitation phase of the estuary of Bilbao has been done based on annual mean DO values averaged for the whole estuary (García-Barcina et al., 2006) and this provides limited information and understanding, since the estuary of Bilbao, as most estuaries, is a complex and heterogeneous system, with areas of very different physiographical and hydrodynamical characteristics, such as the degree of tidal and freshwater influence, the strength of stratification and the residence time, which can affect the rate of oxygen reaeration. In fact, large spatial (axial and vertical) variations in DO were observed even after the implementation of secondary sewage treatment (García-Barcina et al., 2006). In a more recent work axial differences in the dependence of seasonal DO variations on hydro-climatic factors, such as temperature and river discharge, have been shown for this estuary (Iriarte et al., 2010). Several studies have corroborated that both seasonal and inter-annual variations in estuarine density gradients produce important changes in the water quality of estuaries (e.g. Valle-Levinson et al., 1995; Ghezzo et al., 2011; van Damme et al., 2005). Hence, it is clear that, for an adequate assessment of DO dynamics and its causes, measurements should be made on multiple temporal and spatial scales, and that both climate and anthropogenic effects should be analyzed (Rabalais et al., 2010). In view of all these considerations, in the present work we aimed to analyze the spatial (both axial and vertical) variations in temporal changes (both seasonal and inter-annual) of DO in the estuary of Bilbao during the period 1998–2008 and assess the contribution of sewage pollution abatement and hydro-climatic factors to the DO variations, both at seasonal and inter-annual time scales, at different depths and salinity zones along the longitudinal axis of the estuary.

2. Materials and methods

2.1. Study area

The estuary of Bilbao (also known as the Nervión River Estuary) is a small macro-mesotidal system located on the Basque coast in the inner Bay of Biscay (43°23′–43°14′N, 3°07′–2°55′W) (Fig. 1). The estuary is constituted by a 3.8 km wide and 10–30 m deep semi-enclosed embayment known as Abra, which has undergone large harbour developments, followed by an area which has been intensely modified through land reclamation, dredging and channelization, and is at present reduced to a narrow (∼33–270 m wide) ∼14.5 km long artificial channel that crosses urban and industrial areas. Mean river discharge and seawater inflow rate have been calculated to be 0.025 $m^3\,s^{-1}$ and 0.23 $m^3\,l\,s^{-1}$ respectively (Urrutia, 1986). The estuary is partially mixed in the outer part and highly stratified in the inner half (Urrutia, 1986). High salinity waters (>30) usually penetrate as far as the upper reaches at the bottom, whilst freshwater flows seaward at surface and is progressively mixed with seawater (Intxausti et al., 2012). Except for short periods of high river discharge, euhaline waters (salinity >30) dominate within the estuary.

From the mid 19th century to the late 20th century the estuary received large amounts of untreated domestic sewage, mineral sluicing and industrial (mainly iron–steel, chemical, paper) wastes which significantly impoverished its water quality (Belzunce et al., 2004). Hypoxic (and even anoxic) conditions developed throughout extended areas of the intermediate-inner estuary and biological communities underwent dramatic changes with significant losses in biomass and diversity, some inner estuarine areas becoming azoic for many years (González-Oreja and Sáiz-Salinas, 1998; Uriarte and Borja, 2009).

From the late 1980s a sewage treatment plan has been progressively implemented for the metropolitan area of Bilbao. The main wastewater treatment plant (Galindo WWTP) came into operation in 1990 and at present it receives urban wastewaters corresponding to a population of around 1,000,000 inhabitants. Initially the physico-chemical treatment was used, and from 2001 onward secondary treatment began to be applied (Franco et al., 2004). Concomitantly the area has undergone a major industrial decline. As a result, the water quality (García-Barcina et al., 2006), the quality of sediments (Fernández-Ortiz de Vallejuelo et al., 2010) and benthic (Borja et al., 2006; Díez et al., 2009) zooplankton (Villate et al., 2004) and fish communities (Uriarte and Borja, 2009) are progressively improving.

2.2. Sampling and data set acquisition

The data set (1998–2008) used in the present study was obtained in a plankton monitoring programme of Basque coast estuaries. Because of the changing spatial zonation of salinity in the estuary of Bilbao by the effect of tides and river discharge, in this monitoring programme a lagrangian sampling strategy at selected salinity sites was followed, instead of sampling at spatially fixed stations. Thus, samplings were carried out once a month, at high neap tide, in four selected salinity sites in which at ca. mid depth, below the halocline there are waters of salinities of 30 (±1), 33 (±0.5) 34 (±0.5) and 35 (±0.5) in the estuary of Bilbao. The estuary stretch within which each salinity zone was sampled is shown in Fig. 1. Salinity zones were selected because we wanted to describe DO variations in the water masses that define the main pelagic habitats supporting the zooplankton in the estuary of Bilbao (Uriarte and Villate, 2004). At each sampling point vertical profiles (every 0.5 m) of salinity, water temperature and DO-saturation (%) were obtained *in situ* using a WTW multi 350i Multi-Parameter Water Quality Meter. In addition, water samples were collected for chlorophyll *a* analysis at each sampling point from below the halocline. Chlorophyll *a* was measured spectrophotometrically in triplicate samples according to the monochromatic method with acidification (Jeffrey and Mantoura, 1997).

Salinity stratification was estimated in two ways. Salinity stratification index 1 was calculated as the difference between bottom and surface salinities divided by the mean water column salinity, similarly to the n_s stratification parameter described in Haralambidou et al. (2010). The term Salinity stratification index 2 as used in the present work corresponds to the maximum difference in salinity at 0.5 m depth intervals obtained in the water column, and we propose it as an index to reflect the sharpening of the salinity gradient associated to the narrowing of the halocline layer.

In the above mentioned monitoring programme no variable indicative of sewage discharges into the estuary was measured, but ammonia (NH_3–N) data, which can be considered as a proxy of sewage discharge, were provided by the local Water Authority (‘‘Bilbao Bizkaia Water Consortium’’). For the determination of ammonia, surface and bottom (0.5 m above the sediment bed) water samples were collected monthly (generally more than 8 samplings/year) at 8 sampling stations (‘‘Abra exterior’’, ‘‘Abra interior’’, ‘‘Puente Colgante’’, ‘‘Axpe’’, ‘‘Rontegi’’, ‘‘Zorroza’’, ‘‘Deusto’’, ‘‘Arriaga’’ see Fig. 1) located along the estuary. Samples were preserved with chloroform (0.1% v/v) and analyzed for ammonia nitrogen (NH_3–N in μg-at l^{-1}) in an automatic TRAACS 2000 analyzer (Bran + Luebbe) by the phenate colorimetric method (see