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Atlas of susceptibility to pollution in marinas. Application to the Spanish coast

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ABSTRACT

An atlas of susceptibility to pollution of 320 Spanish marinas is provided. Susceptibility is assessed through a simple, fast and low cost empirical method estimating the flushing capacity of marinas. The Complexity Tidal Range Index (CTRI) was selected among eleven empirical methods. The CTRI method was selected by means of statistical analyses because: it contributes to explain the system's variance; it is highly correlated to numerical model results; and, it is sensitive to marinas' location and typology. The process of implementation to the Spanish coast confirmed its usefulness, versatility and adaptability as a tool for the environmental management of marinas worldwide. The atlas of susceptibility, assessed through CTRI values, is an appropriate instrument to prioritize environmental and planning strategies at a regional scale.

1. Introduction

The recreational sailing sector has experienced globally an increasing development in recent years (Davenport and Davenport, 2006). Marinas, scattered along the coast, entail a significant pressure for many regions, posing a relevant impact on their water quality (Di Franco et al., 2011; Yılmaz et al., 2014). Management tools designed to support environmental strategies aimed at improving the water quality in marinas are thus needed (Petrosillo et al., 2009). Moreover, water quality is the single most important environmental consideration in the design of marinas (Smith et al., 2002; Yin et al., 2000). Detrimental effects on water quality within a marina can be avoided by reducing the potential sources of pollutants or by maintaining an optimal flushing rate (Schwartz and Imberger, 1988). The higher the flushing capacity of a marina, the shorter the retention of contaminants, and better the expected water quality (Nilsson and Grelsson, 1995; Orfila et al., 2005; Shen and Haas, 2004). Marinas with an adequate exchange will be less susceptible to pollution, than those with poor mixing (Abdelrhman, 2005; DiLorenzo et al., 1994).

The intrinsic flushing capacity of semi-enclosed aquatic environments, such as marinas, can be expressed by the definition of transport time scales, which describe physical transport and mixing processes (Cucco and Umgiesser, 2006; Cucco et al., 2009). Transport time scales have been widely studied in aquatic systems (e.g. Bárcena et al., 2012; Chen, 2007; Kraines et al., 1999) and harbours (e.g. Gómez et al., 2014a; Sámano et al., 2012) by analysing the transport of a hypothetical tracer by numerically modelled experiments. Numerical models provide high-quality spatial variation results, but they require a great deal of calibration and simulation time and resources (Gómez et al., 2014b). Methods to determine the flushing capacity of marinas at a regional level must be simple enough to be implemented efficiently in a large number of marinas with limited data, but specific enough to preserve the distinct geometry and hydrodynamics of each system (Abdelrhman, 2005). Due to the relative complexity of numerical models, these applications should be preceded by preliminary, screening studies (DiLorenzo et al., 1994).

The scientific literature offers different empirical methods for calculating flushing capacity, based either on hydrodynamic or morphological characteristics. Most hydrodynamic methods are fundamentally based on tidal action (DiLorenzo et al., 1994; Dyer, 1973; EPA, 1985; Nece et al., 1979; Sanford et al., 1992), allowing the differentiation of marinas located at different latitudes. However, although tidal exchange improves the water quality within a basin, this forcing mechanism in itself is not an index of its quality (Nece, 1984). On the other hand, the existing morphological methods consider proportional ratios of two geometric parameters (e.g. area, perimeter or cross section), avoiding the consideration of physical transport and mixing processes. As other authors have demonstrated, the combined use of hydrodynamic and morphological characteristics allows the classification of aquatic systems in terms of environmental processes (Galván et al., 2010; Hume et al., 2007). Hydrodynamic characteristics should allow an estimation of the strength of the driving mechanisms allowing the identification of tidally active marinas, while morphological parameters should allow an estimation of the complexity of the domain, identifying marinas with stagnation zones (dead areas).

The goal of this paper is to develop an empirical method to create a regional atlas of the susceptibility of marinas to pollution. This method should (a) estimate flushing capacity in a cost-effective manner based

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on existing data, (b) be sensitive to the location, typology, physical and hydrodynamic conditions at a given marina, and (c) be correlated with numerical model results. To reach this objective, a detailed collection of data from 320 marinas along the Spanish coast was carried out. The empirical methods developed here were compared with a set of previously published ones as well as with the flushing time obtained using numerical models.

2. Sites description

The study was carried out at 320 marinas located along the 7905 km of Spanish coast (Fig. 1) (FEAPDT, 2016). A database with the main characteristics of each study area was generated.

Globally, marinas along the Spanish coast are mainly located in the Mediterranean ecoregion (60.3%) (Fig. 2). These marinas are mainly placed in coastal areas (95.9%). Conversely, marinas located along the Atlantic Ocean (39.7%) are either coastal (45.7%) or situated in transitional waters (52.0%). Freshwater marinas are represented both in the Atlantic (2.4%) and in the Mediterranean (1.0%) ecoregions.

Marinas are classified into four typologies: i) *harbour*, an artificial shelter constructed for ships normally protected by two breakwaters; ii) *dock*, an area artificially enclosed by docks; iii) *anchorage*, a natural shelter for ships by anchoring, mooring to buoys, or exceptionally, by berthing; and, iv) *interior*, a natural or artificial shelter invading land areas with sea water, normally with a breakwater. All typologies are mainly located in coastal waters of the Mediterranean ecoregion: harbours (57.2%), docks (59.8%), anchorages (59.1%) and interior marinas (46.7%). *Harbour* is the most representative typology at all ecoregions and water categories, except for transitional waters marinas located in the Mediterranean Sea. Harbour is also the only typology found in both ecoregions and in all water categories.

3. Material and methods

3.1. Flushing capacity estimations

Flushing capacity was estimated by means of numerical models and by empirical methods (Table 1). Flushing time (FT), when calculated using numerical models, considers a hypothetical tracer experiment by assuming the domain (marina) as an idealized continuous stirred tank reactor (CSTR) (Monsen et al., 2002). A constant concentration of a conservative tracer is released in each water parcel (or cell) in the domain at $t = 0$, while none is added outside the marina. The removal of the tracer's mass, $M_{(t)}$, follows an exponential process. The FT is the e-folding time, i.e., the time required to reduce the total mass of the tracer in the domain to a factor of e^{-1} (37%) of its original value ($M_{(0)}$) (Table 1). Moreover, seven empirical methodologies based on hydrodynamic (a-e methods) and morphological (f-g methods) characteristics were selected from the scientific literature (references in Table 1). Additionally, four new empirical methodologies (h-k methods), based on hydromorphological characteristics, were developed within this contribution (Table 1).

3.2. Setting up the numerical models

Flushing time was modelled for 10 marinas (Fig. 1), representing both ecoregions and the main marina categories and typologies (Table 2). Sea level elevations, velocities and passive tracer concentration fields were calculated using a 2D circulation model. The computation was carried out on a spatial domain that represents the study area as a finite element grid.

Marina geometry and bathymetry were obtained from shoreline and depth soundings, respectively, from the Navigation Chart information of the Spanish Naval Hydrographical Institute. At each study site, these data were interpolated using a kriging method into an ArcGIS 10.1

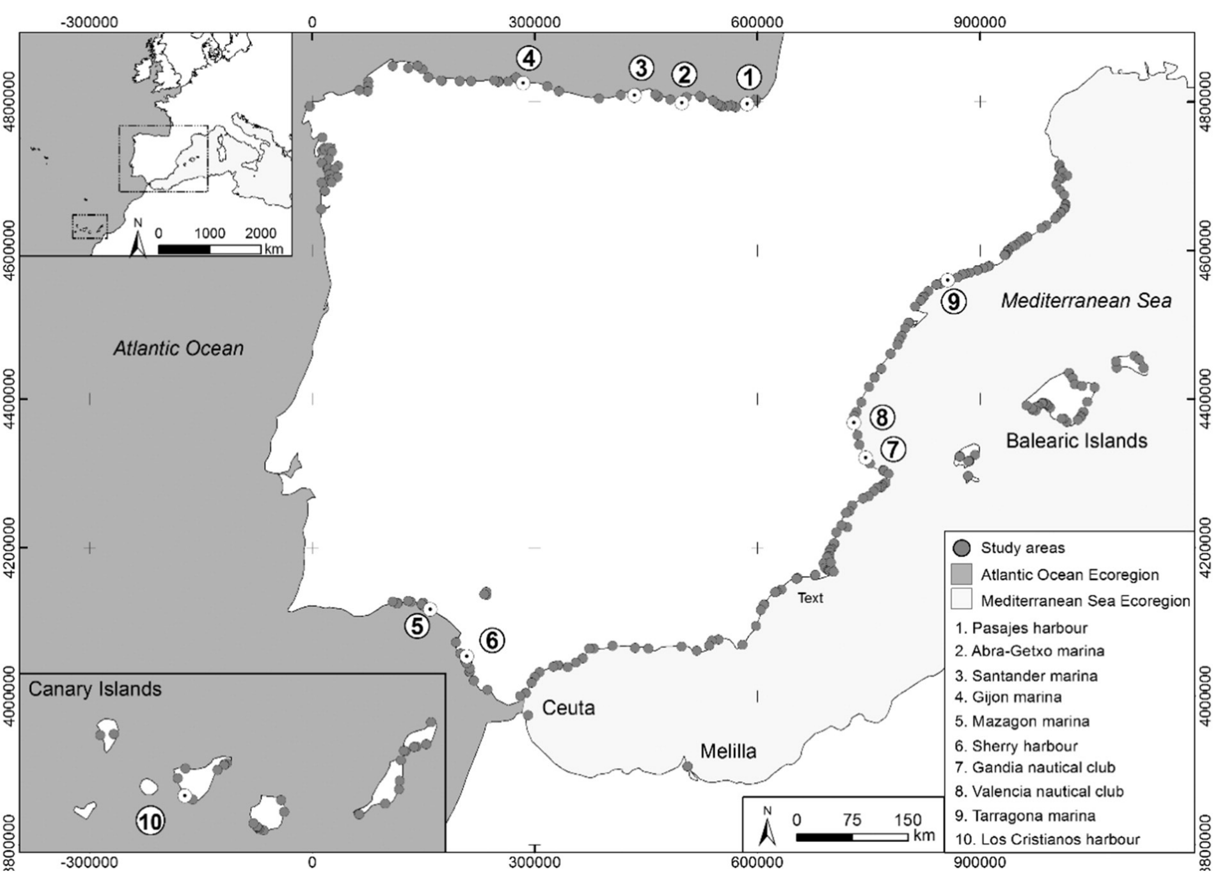

Fig. 1. Location of the study areas (Marinas where flushing time was calculated using numerical models are numbered). UTM coordinate system, projection ETRS89 30 N.