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Transport time scales as physical descriptors to characterize heavily modified water bodies near ports in coastal zones

Aina G. Gómez*, Javier F. Bárcena, José A. Juanes, Bárbara Ondiviela, María L. Sámano

Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, C/ Isabel Torres N° 15, Parque Científico y Tecnológico de Cantabria, 39011 Santander, Spain

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ABSTRACT

Physical descriptors that characterize Heavily Modified Water Bodies (HMWB) based on the presence of ports should assess the degree of water exchange. The main goal of this study is to determine the optimal procedure for estimating Transport Time Scales (TTS) as physical descriptors in order to characterize and manage HMWB near ports in coastal zones. Flushing Time (FT) and Residence Time (RT), using different approaches—analytical and exponential function methods—and different hydrodynamic scenarios, were computed using numerical models. El Musel (Port of Gijon) was selected to test different transport time scales (FT and RT), methods (analytical and exponential function methods) and hydrodynamic conditions (wind and tidal forcings). FT, estimated by the exponential function method while taking into account a real tidal wave and a mean annual regime of wind as hydrodynamic forcing, was determined to be the optimal physical descriptor to characterize HMWB.

1. Introduction

The European Water Framework Directive (Directive, 2000/60/EC, henceforth WFD) established a comprehensive framework for the protection of all waters, with the aim of achieving 'good ecological status' by 2015. Ports with high economic and social value, such as the Port of Gijon, may fail to meet the 'good ecological status' standard. Therefore, the WFD allows for the identification and designation of Heavily Modified Water Bodies (henceforth HMWB), which are bodies of water with characteristics that have been substantially modified as a result of physical alterations from human activity. Once a water body is designated as an HMWB, its status should be based on 'good ecological potential', instead of the 'good ecological status' required to evaluate natural water bodies (CIS, 2006).

The WFD recognizes that the ecological character of surface water bodies varies according to their physical regimes (Harris and Heap, 2007; Jay et al., 2000). However, the WFD does not attempt to provide specific physical descriptors for HMWB. Characterizations of HMWB must be undertaken in accordance with the descriptors of the surface natural water categories that most closely resemble the relevant HMWB. Common descriptors have been used to differentiate several water categories—such as freshwaters (Snelder and Biggs, 2002), groundwaters (Dahl et al., 2007; Vázquez-Suñé et al., 2006), and coastal and transitional waters (Ferreira et al., 2006; Urbanski et al., 2008). However, a typology for HMWB has not been defined yet at European level.

HMWB related to navigation and port activities are primarily associated with hydromorphological alterations (i.e. walls, breakwaters, dikes or wharfs). These physical modifications can significantly alter the hydrodynamic conditions and, consequently, cause variations in the water exchange. Some of the natural water descriptors established in the WFD are related to water exchange—such as current velocity, tidal range or mixing characteristics. Moreover, Transport Time Scales (henceforth TTS)—such as residence time (for lakes and transitional waters) and retention time (for coastal waters)—are proposed. However, the WFD does not define residence time or retention time, and there is no indication of specific methodologies to calculate them.

In that sense, the Spanish guidelines for the planning process of the WFD (Ministerial Order ARM/2656/2008) goes further and establishes Flushing Time (henceforth FT), along with salinity and tidal range, as the physical descriptors to classify HMWB from the presence of ports. The guidelines recommend calculating the FT using i) the classical method—the ratio of the volume of water in

* Corresponding author. Tel.: +34 942201616; fax: +34 942266361.
E-mail addresses: aina.gomez@unican.es, ainagarciagomez@hotmail.com (A.G. Gómez), barcenajf@unican.es (J.F. Bárcena), juanesj@unican.es (J.A. Juanes), ondiviela@unican.es (B. Ondiviela), samanoml@unican.es (M.L. Sámano).

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the domain to the volumetric flow rate through the system; or ii) numerical models—based on the transport of a passive tracer given specific hydrodynamic currents (tide, wind, river, etc.).

At this point, questions arise, such as: which TTS should be used as physical descriptors to characterize HMWB near ports in coastal zones? Which method should be used to calculate them? And which hydrodynamic conditions should be considered?

Scientific literature contains multiple names for TTS (Abdelrhman, 2005; Monsen et al., 2002; Wang et al., 2004), although Residence Time (henceforth RT) and FT are the two most commonly used concepts. RT is defined as the average time required for a volume of a water parcel to leave the domain (Dronkers and Zimmerman, 1982; Hilton et al., 1995; Officer, 1976), and FT is the average time to change all the water in a domain (Monsen et al., 2002). While FT is an integrative parameter that describes the general exchange characteristics, RT accounts for the spatial distribution of water renovation.

Bárcena et al. (2012) and Sámano et al. (2012) proposed using FT in estuarine areas, with numerical models based on riverine and tidal mean values. Both rejected the use of the classical method approach.

Hydrodynamics in coastal waters, such as Gijon, are fundamentally conditioned by tidal action, wind effects, wave-induced currents, density gradients, and river discharges (Essa, 2004). In most studies, currents generated by tide and river discharges are used to calculate TTS (Cucco et al., 2009; Wang et al., 2004; Yuan et al., 2006). However, responses to less energetic driving mechanisms—such as wind-driven circulations, wave-induced currents or density gradients—have seldomly been studied or applied in real systems (Orfila et al., 2005).

Our goal is to determine the optimal procedure for calculating the TTS as a physical descriptor in order to characterize and manage HMWB in coastal zones. To achieve this task, we analyze FT and RT results obtained from different approaches and discuss the effect of hydrodynamic forcing on TTS values with a particular application (El Musel HMWB, Port of Gijon, Spain).

2. Study area

The Port of Gijon has become a link between the Iberian Peninsula and Europe. This port is located in the city of Gijon in the north of Spain (43°34′N, 5°41′W) (Fig. 1). Its location has made it the leading harbor for dry bulk traffic within the Spanish harbor system (González-Marco et al., 2008). Nowadays, the Port of Gijon is a center of activity, ranging from the transport of dangerous cargo to recreational use as bathing waters. From 2010, the Port of Gijon has been immersed in an expansion of port facilities (Fig. 1), including the construction of outer docks with a perimeter of approximately 7 km and over 2 km^2 of new storage area (García et al., 2010).

Two HMWBs were designated at the Port of Gijon: the commercial port ‘El Musel’ and the marina (Fig. 1) (Ondiviela et al., 2012). A third area (the new HMWB in Fig. 1) was designated because of the port’s expansion. ‘El Musel’ was selected to test the different TTS (FT and RT), methods (analytical and exponential function methods), and hydrodynamic conditions (wind and tide forcings). ‘El Musel’ is delimited by an imaginary line that connects the two extreme points of the principal docks, with approximately 160 ha and an average depth of 15 m.

Tides and winds are the main hydrodynamic forcing inside of the ‘El Musel’. Sea level elevation along the Cantabrian Sea is conditioned by the oscillations created by an astronomical semi-diurnal tide, with typical spring–neap cycle tidal ranges varying between approximately 4.8 m (extreme spring) and 0.7 m (extreme neap).

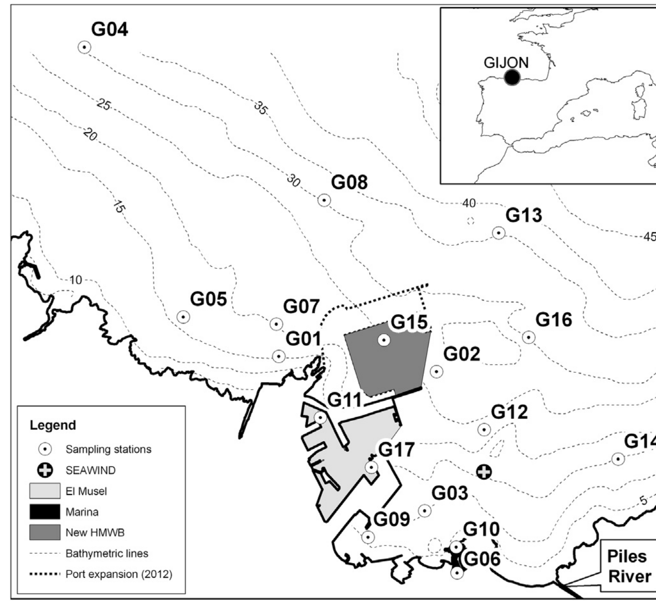

Fig. 1. Location of the HMWB, sampling stations, and bathymetry data in the Port of Gijon.

The most frequent wind events come from the west (17.8%) and northwest (14.5%). Winds from the northeast and east also have a significant presentation probability (over 10%), and are typically associated with good weather conditions. Calm winds (when the wind intensity is below 2 m s^{-1}) represent about 16% of all wind events (García et al., 2010).

The salinity in 17 sampling points along the Gijon harbor was monitored monthly in 2009 by the Port Authority (Fig. 1). Monthly salinity profiles of stations G03, G11, G15, and G17 (Fig. 2), expressed in Practical Salinity Units (PSU), have confirmed that the Gijon coastal area is a well-mixed aquatic system, presenting very low spatial and temporal salinity oscillations—ranging between 34.1 and 35.5. Thus, the use of a 2D model (depth-integrated) could be enough to determine the TTS in this area.

3. Setting up the numerical model

3.1. Model description

Sea level elevations, velocities and passive tracer concentration fields were calculated using a 2D circulation model. The computation is carried out on a spatial domain that represents the study area through a finite-difference grid (Bárcena et al., 2012; García et al., 2010; López et al., 2013; Sámano et al., 2012).

The hydrodynamic module solves the 2D vertically integrated hydrodynamic equations based on the 3D Reynolds Averaged Navier–Stokes equations (frequently termed RANS) for incompressible and unsteady turbulent flows—including the effects of the earth’s rotation, bottom friction, and wind shear. Governing equations are expressed in García et al. (2010), Bárcena et al. (2012), and López et al. (2013).

The transport module (RENOVA) is based on the conservation equation of the quantity of mass of a substance present in the domain. The local variation of the concentration in time was assumed to originate as a consequence of two transport processes: advection (due to the existing hydrodynamic currents) and diffusion (through the effects of turbulent phenomena). Governing equations are described in García et al. (2010), Bárcena et al. (2012), and López et al. (2013).