A risk assessment approach to contaminant emissions in seaport areas: methodological procedure to calculate susceptibility

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Abstract

Water Framework Directive has had a direct impact on the environmental management of port and harbour operations. The response of the Spanish National Port Administration (Puertos del Estado) to environmental responsibilities has been reflected in the well-known Spanish standardisation programme in the field of ports (ROM programme), under the denomination of "ROM 5.1. Quality of coastal waters in seaport areas". Nowadays, ROM 5.1 is put under a process of validation and calibration, being it applied to different harbours in Spain. In terms of risk estimation, calibration process is focused on the estimation of susceptibility of aquatic systems. In this paper, an indicator to estimate susceptibility, a methodological procedure to calculate it, and an evaluation criterion to assess this parameter are established and applied to a Port located in the North of Spain, the Port of Gijon.

Introduction

Due to its immense dimensions and self purification capacity, sea has been used as an unlimited receptor of all kind of contaminants. In recent years, concern has grown over the increase of pollutants discharged into aquatic environment. Different legislation and regulations have been passed with the aim of protecting aquatic environment. The most important outcome, in Europe, has been the Directive 2000/60/EC (henceforth, Water Framework Directive, WFD), which reflects a set of legislation of enormous complexity. WFD establishes a comprehensive framework in the field of water and introduces new principals of modern water management based on long-term protection (Schernewski and Wielgat, 2004). This recent and evolving legislation aimed specifically at protecting the marine environment has had a direct impact on the environmental management of port and harbour operations (Wooldridge et al., 1999).

It is worth mentioning that ports are integrated within cities or towns and their influence cannot be avoided (Ondiviela, 2006). All ports, regardless of their size, have the potential to impact on the environment to a greater or lesser extent depending on their physical characteristics and commercial activities (Revilla et al., 2006). Indeed, it is the great range and diversity of port locations, size, operations, industry base, traffic volume, ownership and local conditions of geography and hydrography that poses such a challenge to the port sector in producing a unified response to the demands of sustainable development and environmental protection (Wooldridge et al., 1999). The response of the Spanish National Port Administration (Puertos del Estado) to environmental responsibilities has been reflected within the well-known Spanish standardisation programme in the field of ports (ROM programme), under the denomination of “ROM 5.1. Quality of coastal waters in seaport areas” (henceforth, ROM 5.1) (Puertos del Estado, 2005).

Due to the preliminary character of the established methodological procedure, ROM 5.1 (available at http://www.puertos.es/es/programa_rom/rom_51_05.html) must be put under a validation and calibration process that allows to solve the possible uncertainties and to value its elements of analysis. This recommendation was published on September 2005, nowadays it is being applied to different harbours in Spain, Port of Gijon (North coast), Port of Tarragona (North-East coast), Port of Huelva (South-West coast) and Port of Tenerife (South-East), to calibrate and validate formulations, equations, parameters, among others.

One of the principal items in this recommendation is environmental risk estimation in port water bodies. In ROM 5.1 the proposed methodology to estimate environmental risk is based on 150008-EX-UNE. Major environmental hazards of coastal waters in seaport areas are contaminant emissions, since these are related to internal and external activities, emitted substances and environmental characteristics (Revilla et al., 2006). Risk estimation, in ROM 5.1, implies the description of these hazards, in terms of their nature and magnitude, by means of determination of occurrence probability, the derived consequences from hazard occurrence and the vulnerability of the environment. The procedure to estimate environmental risk is based on a quantitative method. In this method, probability is calculated by means of frequency of occurrence of the contaminant emission. Estimation of consequences is founded on four parameters: how hazardous the substances are (hazard posed, Fh), the affected extent in each water body by the contaminant emission (extent degree, Fe), how easily water bodies can be restored (potential recovery, Fr) and finally, social repercussion (Fc). On the other hand, vulnerability is calculated by means of three parameters: susceptibility of receptor (Fs), accessibility of contaminant emission (existence of control, defence and alarm systems, Fa) and efficiency of operating procedures to avoid contaminant emissions (Fe) (Puertos del Estado, 2005).

Process of calibration and validation of ROM 5.1., in terms of risk estimation, is focused on the assessment of the susceptibility of receptor (Fs). The field of environmental risk assessment in aquatic systems is full of complex problems (Patton, 1998). For this reason, in order to assure its utility, a specific and standard methodological procedure should be established with the aim of estimating the susceptibility of aquatic systems in a quantitative way and free from subjective considerations. Susceptibility is strictly defined as the inability to resist a particular external influence, a disturbance. In coastal waters, the response of the natural system to independent anthropogenic forcing factors is related to the time taken for the coastal feature to recover its initial conditions (Pethick and Crooks, 2000). Therefore, susceptibility can be related to the cleaning capacity of aquatic systems, in other words, to the time spend by a contaminant inside the domain under study.

Transport time scales are important physical parameters in aquatic systems and constitute a useful tool for representing the exchange or transport processes (Gómez-Gesteira et al., 2003; Takeoka, 1984). For this reason, transport time scales are what control the concentrations and accumulative capacity of all the substances (Ambrosetti et al., 2003). In this work a new transport time scale is defined to assess susceptibility: recovery time, defined as the time needed to reduce completely the conservative tracer concentration released in a water parcel. It is supposed that a contaminant has been introduced in a water parcel, then the water parcel would not be recovered until the whole contaminant has exit the water parcel. So, a water parcel with low recovery time is more susceptible to a pollution impact than one which is well flushed.

As it was mentioned before, nowadays ROM 5.1 is immersed in a calibration process in order to solve the possible uncertainties and to value its elements of analysis. On this matter, the parameter of susceptibility to contaminant emissions in the estimation risk equation has been deeply studied. In this paper, an indicator to estimate susceptibility, a methodological procedure to calculate it by means of numerical models, and an evaluation criterion to assess this parameter are established and applied to a Port located in the North of Spain, the Port of Gijon.

Zone under study

The Port of Gijon is the study area of this work. This port is immersed within the city of Gijon in the North of Spain. Concretely, the zone under study is the geographical area of jurisdiction of the Port of Gijon, named Port Service Zone and defined like the space of land and water necessary to guarantee the development of port uses and activities (Spanish Law 48/2003). Their limits are included between the following meridians and parallels: Length 5º 42,52' W and 5º 38' W and Latitude 43º 37' N and 43º 33' N (Figure 1).

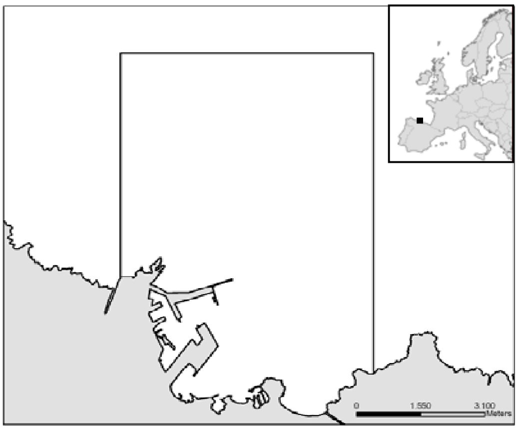

Figure 1: Site under study, geographical area of jurisdiction of the Port of Gijon, located in the North coast of Spain, in the Cantabrian Sea.

Nowadays, the Port of Gijon is more than a basic node of transport system, is a centre of activities, which ranged from the transport of dangerous cargo to recreational use in bathing waters. The surface water of the space scope, with 2950 hectares approximately, is predominantly coastal with protected areas and heavily modified water bodies.

Material and methods

Recovery time is calculated with regard to a hypothetical tracer experiment by means of numerical models. A tracer concentration is instantaneously released inside a water parcel, and zero elsewhere. The concentration of tracer in the water parcel decreases with the time as tidal advection and dispersion act to remove the tracer from the system (Choi and Lee, 2004). Recovery time is estimated by each water parcel inside the site under study, so its spatial distribution is obtained.

Numerical computations are carried out on a spatial domain through a finite element grid. Geometry and bathymetry are defined with shoreline and depth soundings taken from Navigation Charts information. The bathymetric data is obtained from the Naval

Hydrographic Institute. Digitized bathymetry is used to generate the three-dimensional grid used by the finite-element models to predict circulation and transport. The grid contains 20200 cells (92.65m edge), and the area under study has 4505 cells or water parcels (Figure 2).

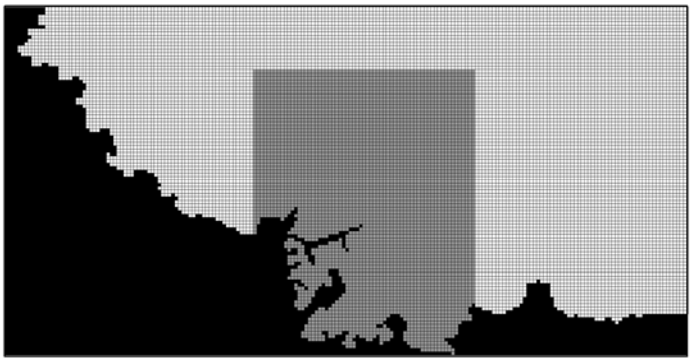

Figure 2: Finite element grid of Port of Gijon and Cantabrian Sea, numerical domain of the model, it has 200x101regular square cells, with 92.65m of edge. Black cells correspond to land and dark grey cells cover the site under study, geographical area of jurisdiction of the Port of Gijon, with 4505 cells or water parcels.

The most important currents forcing, tide and wind, are estimated. A medium tidal wave and a medium annual regime of wind are used. Tidal currents are obtained by means of a two-dimensional numerical model (2HD model) (GIOC, 1990). The model is based on the non-linear shallow-water wave equations and integrates the depth-averaged equations of continuity and momentum. Hourly current velocities in each cell of a medium tidal wave are obtained. Velocities generated by wind are variable in depth, so a quasi-three-dimensional model is used (2DHZ) (Álvarez, 1996). On the other hand, velocities generated in the eight significant wind directions (N, NE, E, SE, S, SW, W and NW) are obtained for two wind representative intensities in the site under study (in this case, 5 and 10m/s). Random regime of winds is considered by means of the application of Monte Carlo method, using probabilities of occurrence per each wind episode (García et al., 2001).

Finally, a two-dimensional transport model is used to study the evolution of conservative tracer concentration in each water parcel or cell. Recovery time per cell is calculated assuming that water parcels can be an idealized flow reactor model such as the continuous stirred tank reactor (CSTR). The major assumption for the CSTR model is that any introduction of mass is instantaneously and evenly mixed through the domain, so the concentration of a constituent exiting the system is equal to the concentration everywhere inside the CSTR. It is assumed that: a) a load of known mass is injected into a CSTR at (time) t = 0 resulting in an initial concentration C0, b) no further mass is introduced after t = 0, and c) water available to flush the domain mixes completely with the existing domain water in each tidal cycle (Cucco and Umgiesser, 2006; Monsen et al., 2002; Thomann and Mueller, 1987; Wang et al., 2004). Water parcel is specified with uniform concentration of a conservative tracer at some instant. As models runs, the tracer is gradually lost. The removal of C(t) will follow a linear process and it is described as:

$$\frac{dC_{(t)}}{dt} = -\gamma C_{(t)} \tag{2}$$

$$C_{(t)} = C_{(0)}\, e^{-\gamma t} \tag{3}$$

$$\ln C_{(t)} = \ln C_{(0)} - \gamma \cdot t \tag{4}$$

Evolution of the concentration of conservative tracer at each water parcel is obtained by computing residual tracer concentration in the water parcel every 20 seconds until most of initial mass has exited. Theoretically, the simulation should be made until the concentration of conservative tracer, in the water parcel, reached value zero. It will take infinitely long time to replace all tracer concentration in the water parcel. For this reason, it is assumed that recovery time is the time required to reduce the concentration in the water parcel to a 0.1%.

Once recovery time is calculated per each water parcel, an evaluation criterion to assess susceptibility to contaminant emissions by means of recovery time results is needed. Due to a spatial distribution is obtained where each water parcel has a specific recovery time, these water parcels need to be classify in the way that permits to distinguish between areas with different susceptibility. Intervals between data are calculated by means of a geometrical interval classification method using ArcGis 9.2®, since distribution of data values is not uniform, data is skewed. This classification method provides intervals which have a geometric sequence based on a multiplier by minimizing the square sum of elements per class, which ensures that each interval has an appropriate number of values within it and the intervals are fairly similar. Each parameter in the risk estimation equation is assessed having into account four levels, so, four intervals are needed to assess susceptibility to contaminant emissions.

Results

Hydrodynamics

The first step to estimate recovery time is the analysis of the hydrodynamic conditions of the marine environment. The currents produced by the tide and the wind have been obtained in a continuous process of simulation. Tidal velocity field are obtained considering medium tidal wave. The random regime of winds has been considered by means of the application of Monte Carlo Method.

An example of the hydrodynamic results is presented in Figure 3. In Figure 3a it is plotted the velocity fields in the area of study in two situations (flood tide and ebb tide). In Figure 3b it is plotted the surface velocity field calculated for a NE and W wind with an intensity of 10 m/s.

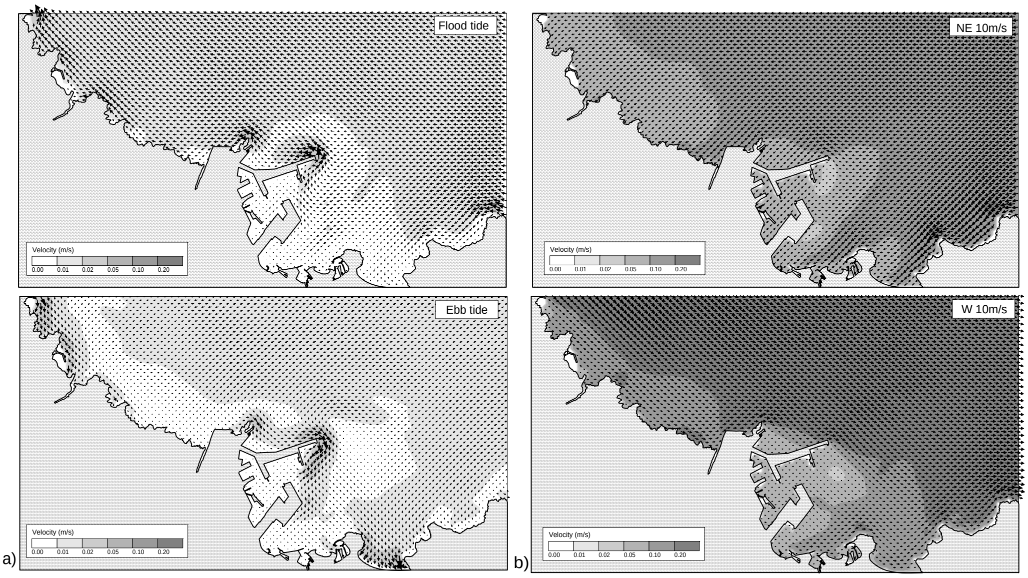

Figure 3: a) Example of velocity field in the area of study in two situations of the tide cycle; b) Surface velocity field produced by a NE and W winds of 10 m/s of intensity.

Recovery time results

Recovery time has been computed for all water parcels inside the site under study, concretely 4505 water parcels (see Figure 2). It is assumed that evolution of the tracer concentration in each water parcel describes an exponential reduction, adjusting to a CSTR. Even though, CSTR is an ideal case which does not completely represent real systems. The behaviour of a water parcel inside the port of Gijon has adjusted fairly well to CSTR system (Figure 4), since normal logarithm of the percentage of tracer concentration in the water parcel fits to Equation 4, with a coefficient of determination of 0.9728 and a recovery time of 79.63 days.

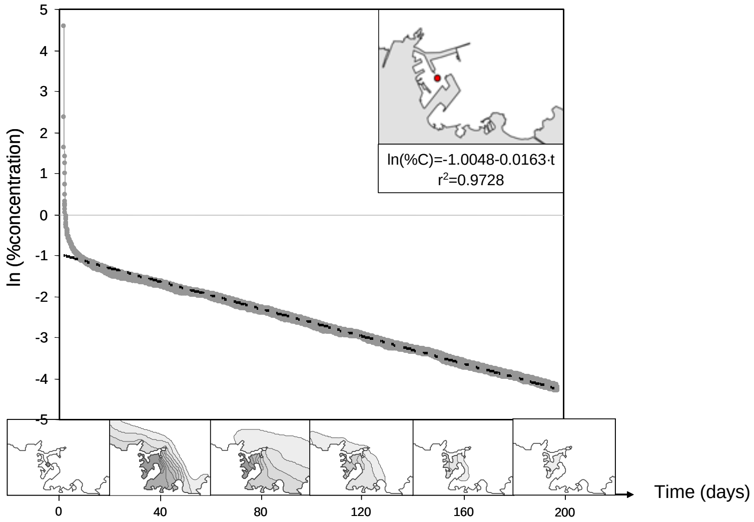

Figure 4: Evolution of natural logarithm of the percentage of tracer concentration in a water parcel located inside the Port of Gijon with a recovery time of 79.63 days, dispersion of conservative tracer concentration is plotted every 40 days.

The transport numerical model makes a sweep of the grid searching water parcels inside the site under study. If the water parcel is located inside the site under study the model calculates its recovery time, if not the model continues sweeping the grid. The numerical model is able to provide a unique file with the spatial distribution of recovery time. In Figure 5 obtained results are plotted, recovery time values show a wide range, from near zero to values over 160 days for water parcels located in the area between docks, where cleaning capacity of water parcels is lower.

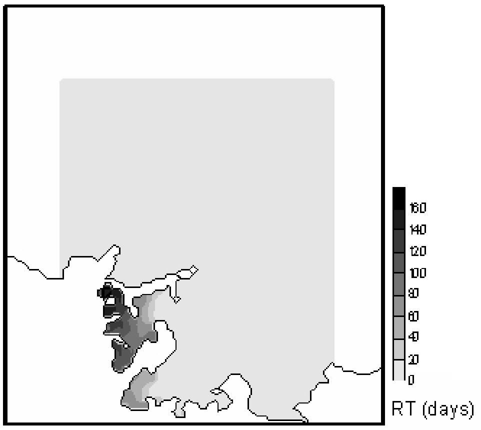

Figure 5: Spatial distribution of recovery time values in the site under study.

As was expected, due to its physical characteristics water parcels located inside confined areas as it is the area between docks in the Port of Gijon have higher recovery time values than water parcels out of these areas where water renovation is quicker. Recovery time values should be translated to susceptibility, since the higher are recovery time values the higher should be the susceptibility. As it was mentioned before, four classes of susceptibility are defined: low susceptibility, moderate susceptibility, high susceptibility and very high susceptibility. So, areas with similar recovery time value should be discretized from the others. For this reason, distribution of recovery time results in the site under study are classified by means of a geometrical interval classification method, which ensures that each interval has an appropriate number of values within it.

Interval limits estimated from the classification method allows classifying water parcels into four kinds of susceptibility based on their recovery time. As it can be seen, interval limits from classification method by means of ArcGis 9.2® are not whole numbers, for this reason, and with the aim of establishing an evaluation criterion easy to remember and simple to apply these have been adjusted to: 1, 7 and 30 days (Table 1).

Susceptibility	Recovery time (days)	
	Limits from classification method	Evaluation criterion (Adjusted limits)
Low	$RT \leq 1.13$	$RT \leq 1$
Moderate	$1.13<RT\leq 6.39$	$1<RT\leq 7$
High	$6.39<RT\leq 32.94$	$7<RT\leq 30$
Very high	$RT>32.94$	$RT>30$

RT: Recovery Time

Table 1: Established evaluation criterion to assess susceptibility by means of recovery time values.

Using this evaluation criterion, four areas are discretized, each one with different potential recovery (Figure 7). As it was expected, the area with very high susceptibility is located inside the commercial port and the zone saved from the dock, these areas have low cleaning capacity, for this reason, a contaminant emission would persist for a long time inside them. High susceptible areas are located close to the coastal fringe, where hydrodynamics conditions do not help to recover these areas in less than seven days. On the other hand, areas with lower susceptibility to contaminant emissions, with moderate and low susceptibility, are placed far from physicals elements and infrastructures that could impeded the movement of water volume and therefore its renovation. So, if a contaminant emission would take place in a water parcel, it would be “clean” in less than seven days

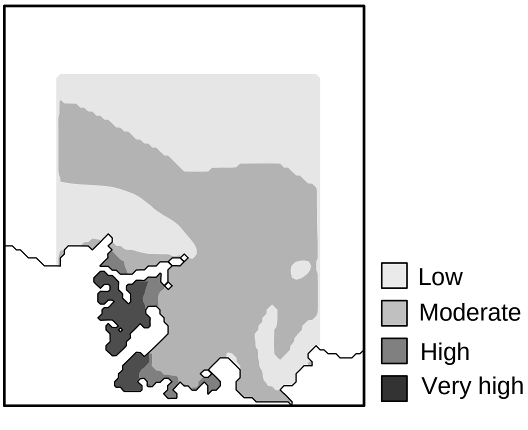

Figure 7: Susceptibility in the site under study, the geographical area of jurisdiction in the Port of Gijon.

Discussion

Transport time scale used to obtain susceptibility should: a) provide a spatial distribution; b) be simple to calculate it, and applicable to any seaport area; c) distinguish between zones with high flushing rates than others with low flushing rates. Aquatic literature contains multiple names for time scales of transport, though; flushing time and residence time are the two more commonly used concepts (Wang *et al.*, 2004, Monsen *et al.*, 2001, Abdelrhman, 2005). Flushing time is considered the average time to change all the water in a domain; thus, flushing time describes the general exchange characteristics of a domain, it does not give a spatial distribution, essential information to assess susceptibility to contaminant emissions. On the other hand, residence time is referred to a water parcel, and usually is defined as the average length of time a water parcel remains within the domain (Wang *et al.*, 2004, Abdelrhman, 2005). Residence time values would be related to the length between where the water parcel was located and the boundaries of the domain. For this reason, it would represent the time needed per each water parcel to exit the domain instead of representing the cleaning capacity of each water parcel. For this reason, both terms, flushing and residence time, were combined to obtain a good indicator to estimate susceptibility in seaport areas: recovery time. It was supposed that if a contaminant is introduced in a water parcel, the water parcel is not recovered until the whole contaminant has exit the water parcel. So, recovery time is the time needed to reduce completely the conservative tracer concentration released in a water parcel.

In this work a methodological procedure has been developed to calculate recovery time by means of numerical models. The rapid advances in computer hardware and software, particularly over the past two decades, have significantly increased the utilisation of numerical models for environmental risk assessment studies and the decision-making process (Harris et al., 2004; McIntyre and Wheather, 2004). Modelling has a potentially valuable role: to predict the response of risk allowing objective management (McIntyre and Wheather, 2004). Anyway, methodological procedure is simple to be implemented to any port, but specific enough to preserve the distinct geometry, hydrodynamics, and transport in each water parcel (Abdelrhman, 2005). So, established methodological procedure permits to estimate spatial distribution of recovery time at any port in a simple and correct way.

Finally, evaluation criterion has been established by means of 4505 results of recovery time in the site under study in the Port of Gijon, these are values enough to establish intervals limits. Even though, to corroborate the use of these limits to assess susceptibility to contaminant emissions in port aquatic systems several studies of recovery time in different ports should be done to adjusted interval limits obtained with results from the port of Gijon with the results from other ports.

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References

Abdelrhman, M. A. (2005). Simplified modelling of flushing and residence times in 42 embayments in New England, USA, with special attention to Greenwich Bay, Rhode Island. Estuarine, Coastal and Shelf Science. 62, 339-351.

Álvarez, César. 1996. Aportaciones metodológicas al estudio de la contaminación litoral originada por vertidos y alivios procedentes de redes de saneamiento urbano. Doctoral Thesis. Departament Ciencias y Técnicas del Agua y del Medio Ambiente, University of Cantabria, Santander.

Ambrosetti, W., Barbanti, L., and Sala, N. (2003). Residence time and physical processes in lakes. Journal of Limnology, 62(1), 1-15.

Choi, K. W., and Lee, J. H. W. (2004) Numerical determination of flushing time for stratified water bodies. Journal of marine systems. 50, 263-281.

Cucco, A., and Umgiesser, G. (2006). Modeling the Venice Lagoon residence time. Ecological modelling, 193, 34-51.

García, A., Revilla, J. A., Juanes, J. A., Álvarez, C., Nikolov, K., and García, R. (2001). Probablistic optimisation of sewer systems. Paper presented at the Third Black Sea International Conference, Varna, Bulgaria.

GIOC. 1990. The H2D long wave propagation model. Santander: Ocean & Coastal Research Group, University of Cantabria.

Gómez-Gesteira, M., deCastro, M., and Prego, R. (2003). Dependence of the water residence time in Ria of Pontevedra (NW Spain) on the seawater inflow and the river discharge. Estuarine, Coastal and Shelf Science, 58, 567-573.

Harris, E. L., Falconer, R. A., and Lin, B. (2004). Modelling hydroenvironmental and health risk assessment parameters along the South Wales Coast. Journal of Environmental Management, 73, 61-70.

McIntyre, N. R., and Wheather, H. S. (2004). A tool risk-based management of surface water quality. Environmental Modeling & Software, 19, 1131-1140.

Monsen, N. E., Cloern, J. E., and Lucas, L. V. (2002). A comment on the use of flushing time, residence time, an age as transport time scales. Limnology an Oceanography, 47(5), 1545-1553.

Ondiviela. B. (2006). Desarrollo de un modelo integral de gestión de la calidad de los sistemas acuáticos portuarios. Doctoral Thesis. IHCantabria. Universidad de Cantabria.

Patton (1998). Environmental risk assessment: tasks and obligations. Human and Ecological Risk Assessment. 4 (3) 657-670.

Pethick, J. S., and Crooks, S. (2000) Development of a coastal vulnerability index: geomorphological prespective. Environmental Conservation. 27 (4) 359-367.

Puertos del Estado (2005). “ROM 5.1-05: Calidad de las aguas litorales en áreas portuarias”. Ministerio de Fomento. 136pp.

Revilla, J. A., Gómez, A. G., García, A., Ondiviela, B., and Juanes, J. A. (2006). A Risk Assessment Approach to Contaminant Emissions in Seaport Areas Using Mathematical Models. International Conference on Mathematical and Statistical Modeling. Ciudad Real. Spain.

Schernewski, G., and Wielgat, M. (2004). Towards a typology for the Baltic Sea. Coastal Reports. 2, 35-52.

Spanish Law 48/2003. (2003). Régimen económico y de prestación de servicios de los puertos de interés general.

Takeoka, H. (1984). Fundamental concepts of exchange and transport time scales in a coastal sea. Continental Shelf Research, 3(3), 311-326.

Thomann. R. V.. Mueller. J. A. (1987). Principles of surface water quality modeling and control: HarperCollins.

Wang, C.-F., Hsu, M.-H., and Kuo, A. Y. (2004). Residence time of the Danshuei River estuary, Taiwan. Estuarine, Coastal and Shelf Science, 60(3), 381-393.

Wooldridge, C. F., McMullen, C., and Howe, V. (1999). Environmental management of ports and harbours-implementation of policy through scientific monitoring. Marine Policy, 23(4-5), 413-425.