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A Risk Assessment Approach to Contaminant Emissions in Seaport Areas Using Mathematical Models

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Abstract

The Water Framework Directive (2000/60/CE) establishes a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. Therefore, European commercial ports are within the space scope of this Directive. For this reason, the Spanish National Ports Administration considered essential and urgent to have available some scientifically and technically robust tools that can contribute to port water management. These tools must be integrated in concordance with the underlying principles of the Directive. This philosophy 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". One of the most important items established in this methodology is the evaluation and management of the environmental risks for port water bodies. The principal objective is to identify the source of pollution and to assess the incidence that each contaminant emission has in the quality of port waters. For estimating the consequences of the contaminant emissions a standard methodological procedure based on the use of mathematical models has been established. In this article the possible sources of uncertainty in the application of this methodology are analysed and some aspects related to the practical implementation of the proposed method are discussed.

Key Words: Water Framework Directive, ROM Programme, harbour, water quality, risk assessment, numerical modelling.

1 Introduction

The coastal space is a limited and scarce asset, with a high economic and natural value. In recent years, the coast has become a zone with high social demand, since it is subject to a growth greater than any other terrestrial space. Therefore, more than a sixty per cent of the world's population live in the coastal fringe. Furthermore, the misunderstanding in the past with respect to the sea led to the

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belief that due to its immense dimensions and self purification capacity it could be used as an unlimited receptor of all kinds of contaminants. For that reason, it is not surprising that seas and oceans have deteriorated enormously due to the failure to take into account both their physical and biological limitations (Gómez *et al.*, 2004).

Nowadays, due to the great social and economic impact of environmental pollution, different legislation and regulations have been passed with the objective of protecting polluted environments and controlling contaminant emissions. Therefore, the European policy is based, principally, on two aspects: definition of quality guidelines in different environments and establishment of discharge limits for dangerous substances (García, 2005).

This set of legislation of enormous complexity is reflected in the Directive 2000/60/EC of the European Parliament and the Council. The directive's objective is to establish a Community framework for the protection and management of the European aquatic environment. This recent and evolving legislation and regulation 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).

Furthermore, different environmental instruments have been created for the operation of interior market. These instruments promote a continuous improvement in the environmental performance and have been applied to different ports. For example, ISO 9000 quality management systems became so important that lack of having implemented a certified quality management system became a trade barrier. Starting with several national norms, the process evolved through to the European-wide EMAS system. Partially, simultaneously with the development of the European EMAS, the ISO 14000 series for environmental management systems was developed as a worldwide, certifiable environmental management system (Labodová, 2004).

It is worth mentioning that ports are integrated within cities or towns and their influence cannot be avoided. The Spanish ports jointly with the rest of European ports have been working since the beginning of nineties in the introduction of environmental requirements in port management. For this reason, in recent years a tendency is observed, since at the same time the authority ports tend to harness their activities and diminish the interferences with the environment. Moreover, port activities try to adapt to society's requirements for environmental conservation and to reach the goal of sustainable development (Ondiviela et al., 2006).

In Spain, ports handle almost five hundred million tonnes of cargo each year shared between 28 authority ports. These range from busy ports such Algeciras with a throughput of over 65 million tonnes or Barcelona with more than 40 million tonnes to small ports like Melilla or Villagarcia. Nevertheless, 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. 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 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”. The Spanish ports’ sector considered it both essential and urgent to make available some scientifically and technically robust methodologies that can contribute to port water body management, since effective implementation of suitable policies requires options and responses based on scientific data derived from appropriate technology and methodology.

The recommendation ROM 5.1. has the objective of tackling the problems of port water quality. ROM 5.1 reflects the philosophy of the Water Framework Directive (henceforth, WFD): “to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater”, taking into account port activities in its general approach. For this reason, ROM 5.1 has been conceived as a first technical methodology for integral management of port water bodies, with direct incidence in design, evaluation and environmental monitoring of infrastructure works, activities and port operations (Puertos del Estado, 2005).

This recommendation establishes an easily implemented methodology within the schemes of port management and economically balanced. The recommendation’s conceptual scheme has been organized in four items: characterization of water body types, environmental risk assessment, monitoring of the ecological and chemical state and contaminant event management (Figure 1).

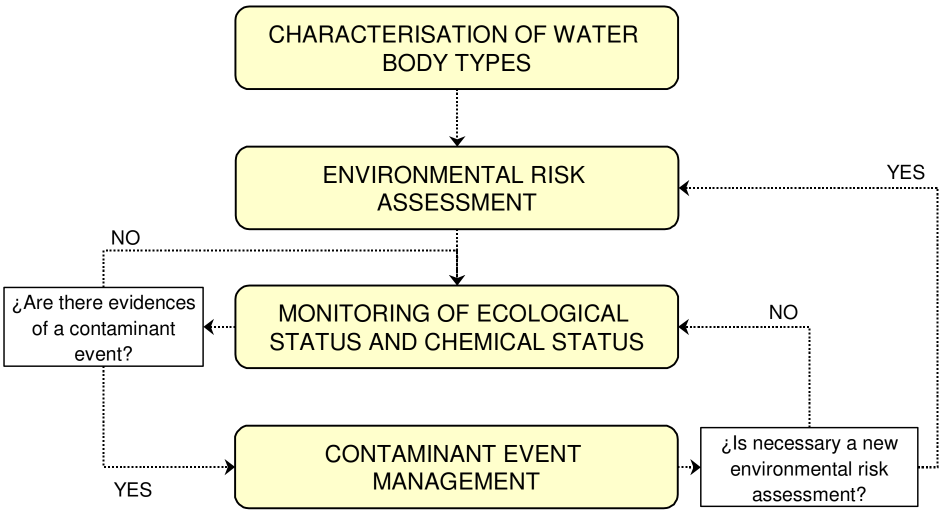

Figure 1: Conceptual scheme of ROM 5.1.”Quality of coastal water in seaport areas”.

One of the most important items established in this methodology is the assessment and environmental risk management for port water bodies. The principal objective in environmental risk assessment is to identify the source of pollution and to assess the incidence that each contaminant emission has on the quality of port waters. The risk assessment process is based on the identification of hazards, estimation and risk evaluation and decision making on an appropriate course of action to manage these risks in a cost-effective manner.

A hazard is a physical situation or condition with the potential to cause harm. Hazard identification is the first and, in many ways, the most important step in risk assessment. The aim of hazard identification is to produce a comprehensive list of all hazards and their characteristics (substances emitted, location, etc.) (Trbojevic and Carr, 2000). In aquatic port ecosystems there are many sources of hazards (chemical, physical, mechanical, biological, human error, natural causes, etc.), but only one type of target, environment, and two ways of hazard transmission, transfer of mass or energy (Labodová, 2004).

Risk estimation is a combination of probability that some (dangerous) event will occur and the consequences of it, if it actually occurs (Labodová, 2004). Traditionally, in surface water quality management, aquatic ecosystem detriment caused by a defined event is simplified to a series of pass-fail criteria, each criterion representing a class of water quality. Historically, environmental risk assessment studies have been undertaken using scaled physical models, sited in large hydraulics laboratories (Harris *et al.*, 2004).

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, therefore, has at least two potentially valuable roles: spatial and temporal criteria can be used in water quality classification rather than discrete, localised measurements of concentration, and to predict the response of risk to changing controls allowing objective management (McIntyre and Wheather, 2004). Therefore, in ROM 5.1 for estimating the hazard consequences a standard methodological procedure based on the use of mathematical models has been established. This methodological procedure permits the estimation of consequences of different hazards in a port water body in a simple and correct way.

The procedures developed in this study closely follow the specifications suggested in the ROM 5.1. This article presents an illustration of a typical port risk assessment study using a fictitious port. The proposed general framework, however, is intended to serve as a template, which can be easily adapted to any contaminant emission in a real port with appropriate modifications of model parameters.

Moreover, in the discussion of the present article the sources of uncertainty in the future application of this methodology in seaports are analysed.

2 Methodology

In ROM 5.1. the proposed methodology for environmental risk assessment is based on 150008-EX-UNE. Environmental risk assessment represents the process of hazard identification and risk estimation. Hazard identification recognizes the existing hazards and their characteristics are defined. On the other hand, risk estimation implies the description of hazards in terms of their nature and magnitude, by means of determination of occurrence probability, environment vulnerability and derived consequences from hazard occurrence. The procedure for estimating environmental risk is based on a quantitative method.

In particular, ROM methodology for estimating hazard impact on the aquatic environment establishes the application of three steps: environmental hazard identification, study of the evolution of contaminant substances based on the use of numerical models and, finally, consequence estimation (Figure 2). Each of these phases is explained in detail in the following sections.

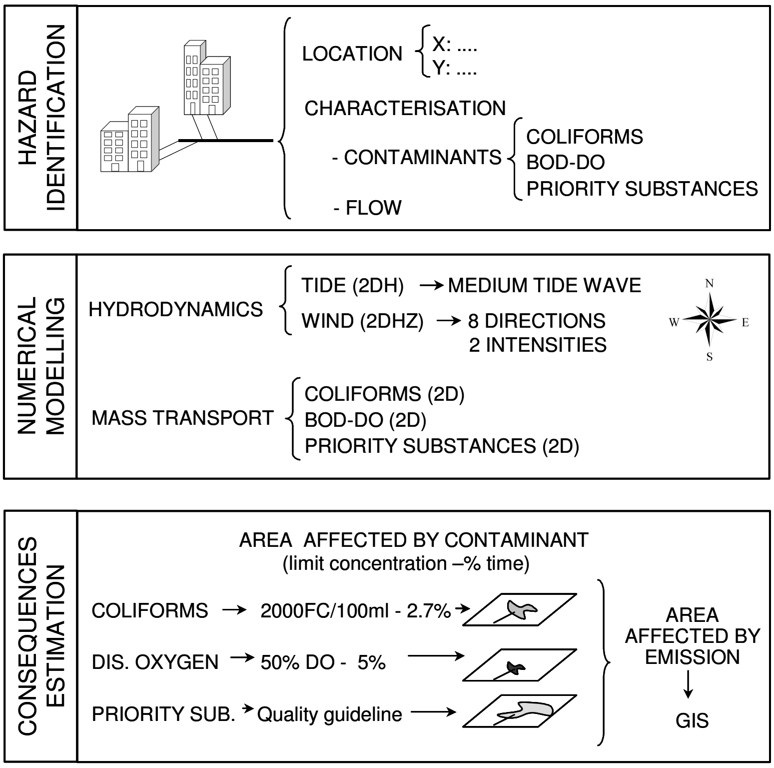

Figure 2: Procedure for consequence estimation of an environmental hazard.

2.1 Environmental Hazard Identification

Environmental hazard identification is the first step in a formal environmental risk assessment. Environmental hazard is commonly defined as any property, condition or situation, of one substance that could cause harm or loss. 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. Contaminant emission in a port aquatic environment is the discharge of substances with potential of affect water body quality. Contaminant emission can be classified as either point or diffuse; point emission is a discharge at a fixed point and diffusive emission is a non channelled discharge.

The basic objective of hazard identification is to obtain the necessary information for carrying out risk estimation. Therefore, any contaminant emission in the port aquatic environment has to be located and characterised. Point emission location is obtained by geographic coordinates, but diffusive emissions are located in the areas where emissions take place.

The emission impact on aquatic system can be divided in three principal pollution types: bacteriological, eutrophication and dangerous substances. ROM 5.1 proposed different indicators for each pollution type: faecal coliforms, biological oxygen demand-oxygen dissolved (BOD-OD) and priority substances (Annex X WFD), respectively. Characterisation of contaminant emission is based on knowledge of the presence of these contaminant substances, substance concentration and emission discharge flow.

Finally, it is worth mentioning that hazard identification is very important since as the more detailed the development of this procedure, the better the estimation of consequences and the more effective the decision making for reducing or eliminating possible impacts in water quality.

2.2 Numerical modelling

The area affected by a contaminant emission is calculated with the aim of knowing its impact on the aquatic environment. Consequence estimation is carried out using numerical models developed by the University of Cantabria. These models allow the calculation of the hydrodynamic currents and the dispersion and decay of the pollutants discharged into aquatic environment (García *et al.*, 2004).

The first step in estimating the contaminant evolution is the analysis of hydrodynamic conditions in the marine environment. The currents produced by tide and wind are obtained in a continuous process of simulation. Tidal currents are obtained by a hydrodynamic depth averaged model (2DH model). Velocities generated by wind are variable in depth, so a quasi-three-dimensional model is used (2DHZ). In this case, the velocities generated in the eight significant wind directions are obtained (N, NE, SE, S, SW, W and NW) for two wind representative intensities of the study zone. The random regime of winds is considered by means of the application of the Monte Carlo method, taking into account the probabilities of occurrence of each wind (García *et al.*, 2001).

Once the hydrodynamic currents are obtained, the study of dispersion of the pollution indicators present in the contaminant emission is carried out. As mentioned before pollution indicators are indicated in the following three groups:

- *Faecal coliforms*: The transport of the bacteriological pollution indicator in the coastal environmental is taken into account by means of a two-dimensional model. The model is able to calculate the evolution of faecal coliform concentration using a decay formula. This formula considers the effects on the decay rate of local factors such as sea water temperature, salinity and solar radiation intensity.
- *BOD-DO*: The evolution of dissolved oxygen is studied by a two-dimensional model which solves the vertical integrated transport equation. The main mechanisms responsible for dissolved oxygen changes in the

water column are included in the model: reaeration, oxidation, benthic sediment demand, respiration and photosynthesis (García *et al.*, 2002).

- *Priority substances*: The dispersion of dangerous substances related to priority substances of the WFD Annex X is calculated by a two-dimensional model considering that these substances are conservative.

Therefore, bacteriological pollution dispersion, dissolved oxygen reduction or priority substances evolution are only modelled if bacteriological, reactive or conservative substances are present in the contaminant emission.

2.3 Consequence estimation

The evolution of every pollution indicator is studied using the model of contaminant emission in a one-year period. So, the affected aquatic area is obtained for each indicator. A zone will be considered affected when at least one of the following conditions takes place:

- *Faecal coliforms*: The breach of bacteriological quality guidelines in protected areas, established in the corresponding norms. For faecal coliforms when concentration is greater than 2000 FC/100ml for more than 2.7% of the time.

- *Dissolved oxygen*: The reduction of the average daily concentration of dissolved oxygen in the water column is less than 50% of the saturation value, for more than 5% of the time.

- *Priority substances*: The breach of some of the established quality guidelines for any priority substances at any time.

Therefore, the contaminant emission impact on the seaport's water quality will be the result of the superposition of affected areas for each pollution indicator. The tool used for estimating the total emission effect is a Geographical Information System (GIS) (ArcView 3.2), in which a specific GIS project (.apr extension) is created for the treatment of results obtained in numerical models, since GIS tools permit the organization and analysis of different data sources in a common platform (Pinho *et al.*, 2004).

The methodology for integrating the geo-referenced hydrodynamics and water quality data into a GIS is based on two simple steps. First, the model file is transformed into polygon entities in shapefile format (SHP) with a viewer, SHP files store location, shapes and attributes of geographic characteristics. The Model's files have point information, for that reason, the second step is to obtain the counter of affected area converting the SHP file into a TIN and then into a grid. Once geographic information has been incorporated into the project, the GIS works as a tool to overlay different affected areas, calculate the surface of affected areas, calculate percentages of water bodies affected and visualize a set of results represented in different layouts.

3 Results

This study has been applied to an fictitious seaport. Two water body can be distinguished in its port aquatic environment (area of Port Authority's jurisdiction): a modified water body contained within dykes and a coastal water body. Hydrodynamic conditions are controlled by semidiurnal tides (about 3m mean tidal range) interacting with wind regime, in which west winds predominate. Two point contaminant emissions located in this port are used for the study: a refinery emission in the modified water body and a wastewater discharge in the coastal water body (Figure 3).

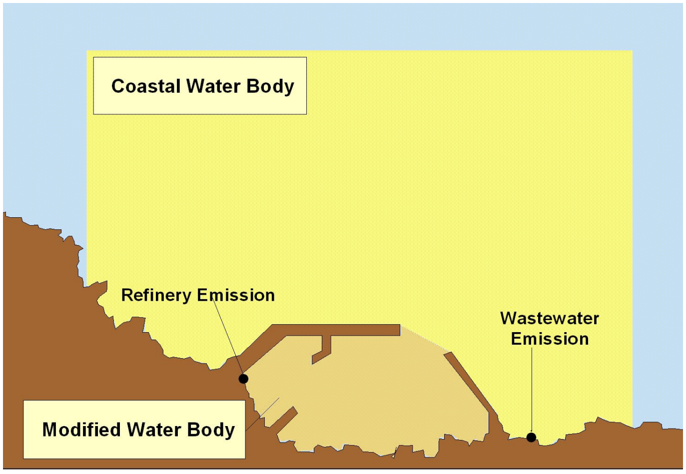

Figure 3: Port characteristics.

On the one hand, the refinery emission emits four priority substances (mercury, nickel, lead and pentaclorophenol) with a discharge flow of $0.5 m^3/s$. On the other hand, the wastewater emission can produce bacteriological pollution and oxygen reduction with a discharge flow of $0.323 m^3/s$ (Table 1).

Table 1. Characteristics of contaminant emission.

Refinery emission		**Wastewater emission**	
Substance	Concentration (mg/l)	Substance	Concentration (mg/l)
Mercury	0.005	Faecal coliforms	$1 \cdot 10^6$ FC/100ml
Nickel	0.1	BOD	325 mg/l
Lead	0.01	OD	0 mg/l
Pentaclorophenol	0.1		

First, for estimating the impact of different indicators of each emission the analysis of hydrodynamic conditions has been done. Tidal currents and free surface elevation over a tidal cycle have been obtained. In relation to wind, current velocities generated in the eight significant wind directions for two wind representative intensities, 5 and 10 m/s have been calculated. An example of the hydrodynamic results obtained is presented in Figure 4, where the surface velocity field calculated is plotted for a northwest wind with an intensity of 5 m/s.

The results of hydrodynamic studies indicate the existence of areas where the velocities are smaller. This aspect will condition the dispersion of pollutants and the size of the area affected by a contaminant emission.

The last step in the consequence estimation corresponds to the study of dispersion of every pollution indicator for each contaminant emission caused by hydrodynamic currents and the decay of the pollutant. As a summary of the results obtained from the dispersion modelling, Figure 5 shows the area affected by each emission.

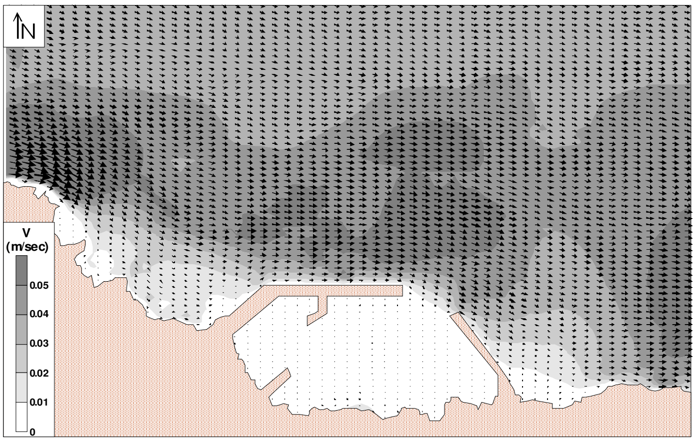

Figure 4: Surface velocity field produced by a northwest wind of 5m/s of intensity.

Figure 5a corresponds to the study of the refinery emission impact. Two of the four priority substances emitted surpass the quality guidelines in aquatic environments: mercury and pentaclorophenol. The modified water body is totally affected by this emission; nevertheless, just 12.5% of the surface of the coastal water body is affected. This is due to emission location, since the discharge takes place inside the modified water body, which is protected from hydrodynamic currents by dykes.

Figure 5b shows the results obtained for wastewater emission in which only faecal coliforms have an effect on the aquatic environment. The emission location is in the coastal water body, and so it just affects the coastal water body.

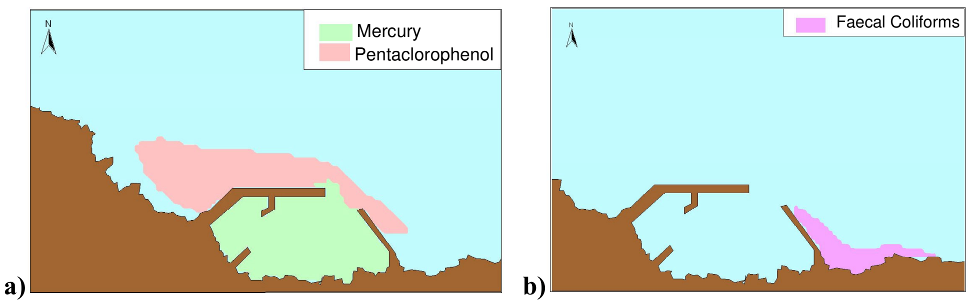

Figure 5: Affected zone by a) refinery emission and b) wastewater emission.

4 Discussion

The ROM 5.1 has been conceived as a first technical methodology for integral management of port water bodies. The established methodology in ROM 5.1. for calculating the risk associated with any contaminant emission situated in the area of Port Authority's jurisdiction is based on the estimation of its probability, its consequences on the aquatic environment and the vulnerability of the affected environment. In this discussion the sources of uncertainty in the future application of this methodology in seaports are analysed.

Firstly, tidal currents are obtained considering a medium tidal wave with constant amplitude. This approach can be an uncertainty source, since, the tide wave is not constant due to the variation of the gravitational pull of the moon and the sun, generating spring and neap tides. However, it should be highlighted that different results could be obtained depending on which tide state the simulation of the transport of contaminant emission begins with. For this reason, it would be necessary to study the effect that the consideration of a medium tidal wave has on the results. Nevertheless, the previously proposed methodology attempts to consider the environmental risk associated with a contaminant emission in medium hydrodynamic conditions. Besides, in order to develop a simple and practical methodology it is supposed negligible the effect of meteorological tide on sea level elevation.

Once the inherent randomness in tide currents using a medium tidal wave is solved, the establishment of the wind regime presents several uncertainties that are detailed next. In the methodology the effect of the wind regime on the dispersion of contaminant substances, a random sequence of wind episodes based on the presentation probabilities of ROM 04-95 is obtained. In order to apply the methodology described which uses numerical tools for taking into account wind effect, the wind regime has to be discretised in a certain number of episodes. The more number of episodes, the more computer resources are used and more calculation time is needed. Altogether in the procedure developed, 17 wind episodes are considered; two intensities for eight wind directions plus a calm situation. Nevertheless, in the ROM 04-95 the wind regime is divided into sixteen wind directions and twelve intensities according to Beaufort units. As indicated before, the reduction of the number of episodes is due to the objective of establishing a simple and practical methodology, since the consideration of all wind episodes established by ROM 04-95 would require obtaining the currents generated by 192 different episodes of wind (16 directions x 12 intensities).

As different studies related with wind data demonstrate that eight wind directions (one for every 45º). This seems a practical approach sufficient for obtaining appropriate results. Thus, the first approach made to reduce the number of the wind episodes has to consider only half of the wind directions. With this simplification the wind episodes are reduced from 192 to 96. However, this value is still too many for a methodology that expects to be of simple application.

Another way of reducing the number of wind episodes is based on the number of wind intensities considered. It should be noted that episodes with a very low probability of appearance would not be represented in a regime obtained by

Monte Carlo method. Considering episodes of eight hours, if a year has 8760 hours in a year there will be 1095 wind episodes. Assuming that the calm situation approximately has an 8% of appearance probability, a wind episode with a probability less than 0.1% would not be included in the random wind sequence. For this reason, it has been considered that for those zones in which the wind rose is homogenous selecting two representative intensities can be assumed sufficient (for example, the Bay of Biscay). Nevertheless, in those zones where a particular quadrant of the wind rose has a probability bigger than 25% it will be necessary to consider three or more intensities for the winds with more probability (for example, The Canary Islands). Considering two representative intensities the number of wind episodes has been reduced from 96 to 16.

The wind effect, since it has been indicated, is represented by a succession of episodes generated randomly. Logically, each wind succession obtained through the Monte Carlo method is different. Thus, depending on the selected wind sequence the results might not be identical. This aspect can be more relevant whichever minor is the extension of the generated sequence, and consequently minor is the number of wind episodes included. If the period duration is short (a month or few months) it would be necessary to model several wind sequences. Thus, initially, to overcome these difficulties in the developed methodology a period of one year is selected. This consideration permits to think that the influence of the wind succession generated is not significant in the obtained results. However, it would not be necessary to simulate a full year, so that a decrease of the simulation period it would reduce computational resources and time required. Therefore, a specific study should be made on the influence of the length of simulation period and the number of wind sequences. It should highlighted that, in any wind sequence, independently of its length, must correspond to the annual average wind regime.

Finally, it is worth mentioning that in order to simplify the methodology it have not been considered other mechanisms generators of currents, like density currents, swell currents, etc.

All these sources of uncertainty are currently the object of a continuing study with the aim of improving the methodology established for the estimation of the consequences of the contaminant emissions in seaport areas.

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