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Environmental risk assessment of water quality in harbor areas: A new methodology applied to European ports

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ABSTRACT

This work presents a standard and unified procedure for assessment of environmental risks at the contaminant source level in port aquatic systems. Using this method, port managers and local authorities will be able to hierarchically classify environmental hazards and proceed with the most suitable management actions. This procedure combines rigorously selected parameters and indicators to estimate the environmental risk of each contaminant source based on its probability, consequences and vulnerability. The spatio-temporal variability of multiple stressors (agents) and receptors (endpoints) is taken into account to provide accurate estimations for application of precisely defined measures. The developed methodology is tested on a wide range of different scenarios via application in six European ports. The validation process confirms its usefulness, versatility and adaptability as a management tool for port water quality in Europe and worldwide.

1. Introduction

Ports are integrated within cities or towns, and their influence is unavoidable (Darbra et al., 2005). Regardless of their size, their environmental impact depends on their physical characteristics and commercial activities. Indeed, the great range and diversity of port locations, size, operations, industry base, traffic volume, ownership and local conditions of geography and hydrography pose 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 quality of aquatic systems in port areas is a consequence of their use and the activities conducted in these environments (Darbra et al., 2004). On many occasions, the interaction of many possible influences makes it difficult to precisely identify the surrounding hazards (stressors), their multiple effects, and consequently, pathways to resolution. It is thus necessary to implement an evaluation procedure that differentiates the sources and effects of the various hazards with the highest possible certainty to proceed with the most suitable management.

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Ports are subjected to modification of management policies that are more heavily orientated towards the use of models in which the economic and environmental factors can be considered as development variables (Bruzzone et al., 2000). Nevertheless, this goal can only be reached using management instruments that integrate the social, economic, legal, technical and environmental demands together with the requirements of the Water Framework Directive (Directive, 2000/60/EC; Wooldridge et al., 1999). In this sense, the first step in the development process is to design a scheme that can answer the three main questions: What must be protected? What does it have to be protected from? How can it be protected?

Environmental risk assessment (ERA) has the potential to become the generalized quantitative tool for environmental management and decision-making at multiple scales (Hope, 2006). That ERA has recently provided a framework to integrate scientists, policy makers, risk assessors and managers in addressing environmental problems (Eduljee, 2000) and represents the processes of: (i) hazard identification, (ii) risk assessment, and (iii) risk management. Hazard identification provides a comprehensive list of all hazards and their characteristics. Environmental risk assessment supplies the description of hazards in terms of their nature and magnitude by determining the probability of occurrence, the vulnerability of the environment and the consequences derived from a hazard. Risk management proposes preventive and corrective measures that should be applied to reduce such risks in a cost-effective manner.

Traditionally, ERA has focused on site-specific or individual chemical questions (Wiegers et al., 1998) and has ignored the spatial structure of the environment, the inclusion of a temporal component, or the presence of multiple stressors and multiple endpoints (Hayes and Landis, 2004). The inherent environment variability must be included in ERA methodologies (Landis, 2003) by, e.g., combining the effects of multiple agents (Lahr and Kooistra, 2010) and considering the ecological properties of receptors (Giupponi et al., 1999) or the temporal evolution of pollutant concentrations (Sala and Vighi, 2008). Several methodologies have been developed to assess environmental risks in harbors, but these methods have only focused on a unique agent (e.g., Gudimov et al., 2010) or hazard (e.g., Ronza et al., 2006), ignored the spatio-temporal variation of receptors and agents (e.g., Trbojevic and Carr, 2000), avoided the ecological characteristics of agents (e.g., Bruzzone et al., 2000), or considered only the impacts generated by accidents (e.g., Grifoll et al., 2011). Moreover, most of the proposed methodologies have not been widely validated by applications in different harbors to develop partial responses to specific scenarios.

To overcome these limitations, based on previous studies and developed methodologies (Gómez et al., 2012; Ondiviela et al., 2012; Revilla et al., 2007), this work presents a general framework of ERA for port water bodies. The main contributions of this study are: (i) the development of a standard and unified ERA methodology to assess environmental risks in port aquatic systems and (ii) the implementation of the ERA methodology in six European harbors.

2. The ERA methodology

2.1. Environmental hazard identification

An objective, user-friendly and systematic method is presented to identify the environmental hazards to water quality in port areas. The matrix shown in Table 1 represents all of the interdependences among a set of defined port infrastructures, equipment and uses vs. each situation that is liable to cause discharge into the water column (Gómez et al., 2012; Juanes et al., 2013). Once the matrix is filled in, port managers have a complete view of all environmental hazards that could have an impact on the water quality.

Contaminant sources from the environmental hazards identified in Table 1 are classified by considering two aspects: method of discharge and origin (Table 2). Contaminant sources are defined as any discharge of substances, elements or energy with the potential to affect water quality in a port area. Classification of contaminant sources allows prioritization of the following work. Internal contaminant sources from port activities and concessionaries or authorized enterprises must be subjected to thorough study because they have the direct potential to affect the water quality in the Port Jurisdiction Area (PJA).

Finally, an intuitive and easy-to-use form (Fig. 1) is presented to gather the required information of each contaminant source for estimating the probability and consequences. Different sources can be consulted to obtain the information, including: (i) discharge authorization, (ii) historical data, (iii) port manager knowledge, (iv) Pollutant Release and Transfer Register (PRTR), (v) emission factors, (vi) specific data acquisition surveys or (vii) matrix activities and substances discharged.

2.2. Environmental risk assessment

Environmental risk assessment at a contaminant source level is based on a multi-metric index following the formula (Equation (1)):

$$R_i = P_i \times V_i \times C_i \tag{1}$$

where *R* is environmental risk, *P* is probability, *V* is vulnerability, and *C* is consequences at contaminant source *i*.

Based on risk estimation, contaminant sources are categorized considering to the following tolerability criteria: (i) *high-risk contaminant sources* ($R_i > 30$) require a study of the problems associated with the risk and immediate adoption of the necessary preventive and corrective measures, (ii) *moderate-risk contaminant sources* ($10 < R_i \le 30$) require a study of the problems associated with the risk and evaluation of the need to implement immediate full or partial preventive and corrective measures, and (iii) *low-risk contaminant sources* ($R_i \le 10$) do not require any special action.

2.2.1. Probability

Probability is defined as a measure of the likelihood that an environmental hazard will occur and is estimated as the frequency of occurrence of the contaminant source discharge (Juanes et al., 2013) (Table 3).

2.2.2. Vulnerability

Vulnerability is referred to the system's characteristics and its potential for harm. Thus, vulnerability is expressed in terms of functional relationships between the environment's *susceptibility* against a disturbance and the *state of conservation* related to the value of the receptors at risk following the formula (Equation (2)):

$$V_i = 1/3\left[\underbrace{2 \times SU_i}_{\text{Susceptibility}} + \underbrace{1/3 \times (NA_i + 2 \times EV_i)}_{\text{State of conservation}}\right] \tag{2}$$

where *SU* is susceptibility, *NA* is naturalness and *EV* is the ecological value of the environment relative to a contaminant source *i*.

Table 3 shows the indicators, metrics and assessment criteria for each parameter. *Susceptibility* is generally defined as the capacity of the environment to assimilate an external influence. Susceptibility to pollution can be related to the time required to recover its initial conditions, i.e., cleaning capacity (flushing time) (Gómez et al., 2012, 2014a). At the same time, the *state of conservation* of physical, biological and chemical processes and elements of the environment are considered as a combination of *naturalness* and *ecological value*. *Naturalness* is defined as the absence of physical anthropogenic modifications. Altered areas around identified hidromporphological pressures are computed to assess it (Gómez et al., 2014b). *Ecological value* is defined as the building capacity of a certain area to support species of flora and fauna. Bearing in mind this definition, ecological value estimation is based on the recognition of ecologically remarkable elements (protected areas) (Gómez et al., 2014b).

2.2.3. Consequences

Consequences are defined as the impact on the environment or social damage/improvement that may result from an environmental hazard. Therefore, the consequences are expressed in terms of the impact to the environment (discharge impact) and to the society (social impact) following the formula (Equation (3)):

$$C_i = 1/3\left[\underbrace{(HZ_i + EX_i)}_{\text{Discharge impact}} + \underbrace{1/2 \times (AM_i + SR_i)}_{\text{Social impact}}\right] \tag{3}$$