Marine Pollution Bulletin 111 (2016) 57–67

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Prioritization maps: The integration of environmental risks to manage water quality in harbor areas

Paloma F. Valdor *, Aina G. Gómez, Bárbara Ondiviela, Araceli Puente, José A. Juanes

Environmental Hydraulics Institute, Universidad de Cantabria, Avda. Isabel Torres, 15, Parque Científico y Tecnológico de Cantabria, 39011 Santander, Spain

ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form 12 July 2016
Accepted 16 July 2016
Available online 27 July 2016

Keywords:
Harbor areas
Risk maps
Cost-effective management
Multiple stressors
Integration

ABSTRACT

A method to integrate the environmental risk of the multiple effects from uses and activities developed in harbor areas is presented. Consequences are considered as the effects derived from all identified hazards. Vulnerability is expressed in terms of functional relations between environmental susceptibility against a disturbance and the state of protection of the receptors at risk. Consequences and vulnerability are integrated obtaining a spatial variation of risk: prioritization maps. The maps are developed by 4 main stages: (1) environmental hazard identification; (2) estimation of the consequences; (3) estimation of vulnerability and, (4) integration of environmental risks. To adapt prioritization maps to the peculiarities of the study area, three different methods for the integration of the effects are proposed: average-value, worst-case and weighted methods. The implementation to a real case (Tarragona harbor, NE Spain) confirms its usefulness as a risk analysis tool to communicate and support water quality management in harbors.

1. Introduction

Activities and uses developed in harbor areas have been widely recognised as services of special economic and social relevance. Commercial, nautical-recreational, logistic and storage uses, among others, are developed all together in the surrounding harbor area. Such coexistence of uses in harbor environments has had negative effects on the aquatic environment (Darbra and Casal, 2004) that can be perceived both spatially and temporally. Harbor areas are affected by multiple stressors coming from a great variety of environmental hazards. Adequate tools to estimate the impact of multiple hazards and stressors on harbors are required.

The effects of environmental hazards on water quality caused by ordinary activities (e.g. Gómez et al., 2015; Ondiviela et al., 2012) as well as uncontrolled spills in harbor areas (e.g. Grifoll et al., 2010; Mestres et al., 2010; Ondiviela et al., 2012) have been widely studied and procedures to provide sustainable solutions without undermining the economy on which the harbor area is sustained have been proposed (e.g. Gómez et al., 2015; Juanes et al., 2013; Ondiviela et al., 2012). But such studies have only focused on a unique stressor (e.g., Gudimov et al., 2010) or hazard (e.g., Abascal et al., 2010; Castanedo et al., 2009; Ronza et al., 2006; Valdor et al., 2015), obviating its integration (Gómez et al., 2014a, 2015), ignoring the spatial-temporal variation of receptors and agents (e.g., Trbojevic and Carr, 2000), avoiding the ecological characteristics of the receptors at risk (e.g., Bruzzone et al., 2000) or considering only the impacts generated by accidents (e.g., Grifoll et al., 2010).

Previously developed methods have mainly focused on point contaminant sources deriving from ordinary activities. None of the actual methodologies combine the effects of regular contaminant sources with accidents. European guidelines and legislation promote the inclusion of specific information on the anticipated effects of accidental spills in management tools (European Commission, 2013; European Commission, 2014; IMO, 1991; IMO, 2000; IMO, 2010). Pollutant incidents due to operational deficiencies, as well as diffuse contaminant sources, should be incorporated in the environmental risk process. This way, all environmental hazards would be considered and best-decision measures could be ensured.

Several national and international institutions have recognised the need to evaluate risk from mixtures and multiple stressors (European Scientific Committees, 2011; NRC, 1994; Mileson et al., 1999; US EPA, 2003; WHO, 2009). While an individual impact assessment outcome may not result in excessive impacts on its own, a combination of the outcomes may cause significant adverse impacts (European Commission, 2010). This combined effect from various stressors on the environment differs from the effect of a single stressor (Velleux et al., 2008). Risk assessment of single stressors need to be adapted and

* Corresponding author at: Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, C/Isabel Torres N° 15, Parque Científico y Tecnológico de Cantabria, 39011 Santander, Spain.

E-mail addresses: fernandezvp@unican.es (P.F. Valdor), aina.gomez@unican.es (A.G. Gómez), barbara.ondiviela@unican.es (B. Ondiviela), puentea@unican.es (A. Puente), antonio.juanes@unican.es (J.A. Juanes).

http://dx.doi.org/10.1016/j.marpolbul.2016.07.028

extended to deal with the specific challenges posed by mixtures (Løkke et al., 2013). Therefore, the overall effect of the various hazards must combine the effects of each of the stressors (Lahr and Kooistra, 2010).

The different integration models (e.g. similar action, independent action) provide a heterogeneous assessment. In a regulatory perspective addressing the cumulative effect of co-occurring chemicals is the first and most important step in providing a more realistic hazard assessment of chemical cocktails in both man and environment (Cedergreen, 2014). The integration method is a crucial aspect in the calculation of cumulative environmental risk (Gómez, 2010), and must be adapted to the purpose of managing:

- What hazards are affecting the most port aquatic systems?;
- What stressors are affecting a specific area of the harbor?;
- How much each facility contributes to the cumulative effect?.

Answering these questions will allow managers to prioritise the various hazards, stressors and facilities in order to apply specific corrective and preventive measures.

The estimation of spatial-temporal environmental risk involves: i) the estimation of the consequences and, ii) the environmental vulnerability (Gómez et al., 2015). Consequences are considered as the effects derived from all identified hazards. The estimation of the spatial-temporal effects requires the study of the stressors spilled from hazards to calculate their trajectory and the potential area affected (Valdor et al., 2015). Calibrated numerical models or tools in Geographical Information Systems are extensively used to simulate the evolution of stressors (Gómez, 2010; Horiguchi et al., 2006; Wania and Mackay, 1999; Yamamoto et al., 2009; Valdor et al., 2016). On the other hand, vulnerability should be addressed in terms of functional relationships between the physical characteristics of the system (extrinsic vulnerability) and the state of conservation (inherent vulnerability) (Gómez, 2010; Gómez et al., 2014a, 2015; Kvaerner et al., 2006). By means of the integration of consequences and vulnerability, prioritization maps would serve as reference for the development of contingency plans (Abascal et al., 2010; Santos et al., 2013), designing environmental monitoring programs and management of environmental hazards as a whole.

To overcome these limitations, the paper develops a methodology to integrate the environmental risk of multiple effects from various hazards on harbor aquatic systems. The method as a whole was tested by application to the Tarragona harbor (NE Spain), analysing the relationship between environmental quality indicators and risk values. This work is based on the hypothesis that activities and uses developed in harbor areas generate cumulative effects caused by multiple stressors which are introduced by point and diffuse contaminant sources (ordinary operations) as well as by pollutant incidents (operation developed under unfavourable conditions). Accordingly, the environmental management of these areas must be carried out in an integrated manner.

2. Methodology proposed

Prioritization maps are made up of 4 main stages: (1) an environmental hazard identification; (2) the estimation of the consequences (cumulative effects); (3) the estimation of the vulnerability (environmental characteristics) and, (4) the integration of environmental risks (prioritization maps).

2.1. Environmental hazard identification

The identification of hazards comprises their systematic location and characterisation. This way, the stressors that are likely to cause deleterious effects to water quality are recognised. Environmental hazards to be considered are: point contaminant sources (predefined fixed points), diffuse contaminant sources (non-challenged discharges) and, pollutant incident sources (accidental spills).

Table 1
Identification of facilities liable to cause pollutant incidents.

Hazardousness	Frequency High (>1 incident/month)	 Medium (>1 incident/year)	 Low (<1 incident/year)
Very High*	✔	✔	✔
High*	✔	✔	✔
Moderate*	✔	✔	✖
Low*	✔	✖	✖

✔ : Facilities identified as potential pollutant incidents.
✖ : Facilities not considered as potential pollutant incidents.
Very high*: Priority hazardous substances (Directive 2008/105/EC)
High*: Priority substances (Directive 2013/39/EC)
Moderate*: Dangerous materials (IMO, 2014)
Low*: Potentially dangerous materials and other materials (IMO, 2014).

Point and diffuse contaminant sources are characterised by gathering the necessary information (location, substances or materials discharged, flows, quantities handled, etc.) by consulting different sources (discharge authorisation, Pollutant Release and Transfer Register (PRTR) and emission factors, local database of accidental spills, among others) (Gómez et al., 2015).

Potential pollutant incident sources are selected from the analysis of local databases of accidental spills. To do this, the next steps should be followed: i) the hazard level (hazardousness) of the substances or materials handled at each facility is defined. The assessment criteria to assign the facility hazard level is shown in Table 1 caption; iii) a frequency of occurrence is estimated to each facility. The assessment criteria for the occurrence frequency term is shown in Table 1; iv) both factors (the highest hazardousness of material or substances handled and the frequency) are combined as shown in Table 1; and, v) facilities with significant frequency of incidents and relevant hazardousness are identified as potential pollutant incidents sources following the Table 1 assessment criteria.

2.2. Estimation of cumulative effects: consequences

The consequences (Co_{ij}) are defined as the cumulative effects on the environment that may result from all environmental hazards. A mesh grid is created with the desired cell resolution comprising the study area. Effects are estimated at cell level obtaining a spatial variation. The integration is made up of 3 levels of integration (Fig. 1): (1) the effect of single stressors; (2) the global effects of each type of hazard; and, (3) the cumulative effects caused by all hazards.

2.2.1. Stressors' effects

The effects of stressors introduced by the various environmental hazards are estimated. The effects of the stressors introduced by ***point contaminant sources*** are estimated in terms of ecological effects of three processes: (i) chemical pollution process caused by priority substances; (ii) eutrophication process measured by the decrease of dissolved oxygen; and, (iii) bacteriological contamination process using *Escherichia coli* as indicator (Gómez, 2010; Juanes et al., 2013). Spatial and temporal evolution of each stressor introduced by single point contaminant sources is calculated by means of numerical models through one year of simulation (Thomann and Mueller, 1987).

For every stressor, acute and chronic effects are computed at cell level (Gómez et al., 2014b):

- Acute effects:

$$\%_{i,j} = \frac{\text{T adverse conditions}_{ij}}{\text{T total}} \times 100 \quad (1)$$