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An oil risk management system based on high-resolution hazard and vulnerability calculations

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ABSTRACT

A new oil risk management system is proposed herein. Risk is computed in a quantitative way, combining a detailed hazard maps generated with a process-based oil spill model over an unstructured computational grid, and a spatially detailed methodology for vulnerability analysis. The system has a web interface that serves as a single point of access to both emergency-driven and risk-management products. The system's products are made available to decision makers and emergency response agents through a WebGIS portal. The paper describes the methodological bases and application of a risk-assessment tool that provides hazard, vulnerability and risk assessment maps for oil spills in coastal areas.

The system is demonstrated in the Aveiro lagoon. The hazard maps are obtained from the analysis of an oil spill scenarios database, generated for the climatological conditions most prone to the occurrence of an oil spill event in the study region. Several vulnerability indexes are considered (namely physical, socio-economical, biological and global vulnerability indexes) and adapted to consider the intertidal areas, instead of the commonly-used coastline representation of the vulnerability indexes usually found in the literature. This new feature was possible due to the capability of the oil spill model to represent the process of oil retention and re-suspension in the intertidal zones.

The methodology and the risk management system and its WebGIS interface are of generic nature and can be applied to other hazards in coastal zones.

1. Introduction

The potentially devastating consequences of accidental oil and chemical spills on the coastal environment raise a growing concern on the preparedness and response to spill-induced emergencies. This concern fuelled the implementation of several support tools, including pollution monitoring systems (Kingston, 2002; de la Huz et al., 2005; Penela-Arenaz et al., 2009) and modelling systems (Abascal et al., 2007; Azevedo et al., 2009, 2014; Wang and Shen, 2010; Liu et al., 2013). However, in the event of a spill accident that affects coastal resources, each tool is mostly used in a disconnected, ad-hoc fashion, without compliance to the risk management cycle, and often not providing accurate predictions at the right scales due to computational constrains or unknown local conditions. Coastal pollution risk prevention is usually based on contingency plans (Sanchez, 2008; Lee and Jung, 2013), supported by studies mostly based on simplified tools, applied in simplified settings and often disregarding local environmental and socio-economic conditions that may promote spill accidents and increase their impacts.

Risk management information technology systems were proposed to support planning and emergencies (Chrastanskya et al., 2009) and have been successfully applied to several risks, such as tsunamis (Careem et al., 2006), and dam-break (Rodrigues et al., 2002; Jesus et al., 2010) and coastal inundations (Fortunato et al., in press). These management systems can be used for oil pollution risks to provide an adequate framework for the effective protection of coastal resources. Their application to accidental oil spills

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requires adaptation on the phases of preparedness and response. To properly plan, through contingency plans, or to forecast spill accidents requires the ability to quantify the relevant environmental conditions that may promote accident occurrence at the adequate spatial scale, through data or numerical models, and to characterize accurately the relevant processes. Recent developments on the efficiency of high-resolution modelling systems for coastal problems using high-performance resources (Costa et al., 2009; Dietrich et al., 2012; Azevedo et al., 2014) paves the way to their application to pollution risk analysis.

The terminology and concepts broadly involved in risk assessment are however often ambiguous and even controversial in the scientific community, mainly due their extended use in different sciences and the lack of standardization. Only in recent years have authoritative agencies begun to compile the major vocabularies, such as hazard, vulnerability and risk (Christensen et al., 2003). The concept of *hazard* relates to the probability of occurrence of a natural or anthropogenic event within a given time period and affecting a specified area, and to the impact of this event on the environment or society (Cutter, 1993; UN/ISDR, 2004). This term is often defined as a threatening event (UN/ISDR, 2004) or a source of potential damage and possible risk source (ISO Guide 73, 2009b), which may cause property damage, economic loss, environmental degradation or loss of human lives. Sources of hazard resulting from human activities that cause or enhance unexpected accidents (e.g. the spill of oil or other dangerous substances) are designated as technological hazards (Zêzere et al., 2008).

According to the International Organization for Standardization (ISO Guide 73, 2009b), *vulnerability* is the intrinsic property of the exposed elements that derives from their susceptibility to a risk source, which can lead to an event with a negative consequence. This term can also be defined as the expected degree of loss of exposed elements resulting from a potentially damaging event (UN/ISDR, 2004; Kumpulainen, 2006; Schmidt et al., 2011). Simultaneously, this term can be associated with the susceptibility and resilience of the exposed elements to negative impacts from hazardous events (NOAA, 1999, mentioned in Andrade et al., 2010). Thus, vulnerability depends not only on the resistance of the exposed elements to the potential damage, but also on the resilience of those elements after the occurrence of the event (Salter, 1997; Kleissen et al., 2007; Lahr and Kooistra, 2010).

The concept of *risk* can be understood as the expected losses due to the occurrence of the adverse event for a given time period and specified area, that result from the interaction between the natural or anthropogenic hazard and the vulnerable assets (UN/ISDR, 2004; De-Lange et al., 2010). Additionally, other authors (Ansell and Wharton, 1992; Tarrant, 1998; ISO Guide 73, 2009b; Lee and Jung, 2013) define *risk* as the product between the likelihood associated with the occurrence of the events and the consequences on the exposed elements, often estimated by hazard and vulnerability, respectively – an approach conceptually appropriate and widely accepted (De-Lange et al., 2010; UN/ISDR, 2004; Xiaoyan and Xiaofei, 2012). Some studies (e.g. Schwab et al., 1998; Douglas, 2007; Garcia et al., 2013) consider the inclusion of another term in the expression: the exposure of elements. This term can be described by several indicators such as the duration of exposure or the concentration or type of substance whose presence promotes danger (Kleissen et al., 2007).

Risk assessment, one of the stages of risk management, involves identifying how exposed elements may be affected and the probability of occurrence of these adverse effects (ISO/IEC 31010). Within oil spill risk assessments, many researchers have targeted several themes: the marine pollution (e.g. Grifoll et al., 2010; Olita et al., 2012; Liu et al., 2013), the harbour areas (e.g. Rao and Raghavan, 1996; Trbojevic and Carr, 2000; Ronza et al., 2006) and the maritime transportation (e.g. Iakovou, 2001; Eide et al., 2007; van Dorp and Merrick, 2011), following very diverse approaches.

According to van Westen et al. (2006), risk assessment methods can be split into three categories: (i) quantitative methods – which determine the probability and consequences of possible loss or damage in numerical and quantitative terms; (ii) qualitative methods - based on an expert opinion to estimate the probability and consequences of potential loss or damage in qualitative terms; and (iii) semi-quantitative methods – which combine quantitative methods (when possible) with qualitative methods. While quantitative methods are the most appropriate and practical approach to risk assessment, applying them to all exposed elements and sources of hazard remains impossible in many cases (EcoRA, 2013). Semi-quantitative methods are thus often a good viable alternative. Although these methods are more subjective, they may be sufficient and suitable to risk assessment depending on the decisions to be taken and the resources available (EcoRA, 2013; IPIECA, 2013). The method to be used should be chosen in accordance with the purpose and nature of the problem and the quality and quantity of data that are available for the risk analysis (Dai et al., 2002; Zêzere and Garcia, 2013).

Several risk assessment studies based on quantitative methods can be referenced. Grifoll et al. (2010) focus on the degradation of the water quality in harbour areas. These authors developed a method for environmental risk assessment that determines risk using indexes that reflect different issues, such as the substance of a potential spill, the probability of occurrence of the events, and the water currents and renewal in the harbour area. Regarding oil spill risk assessment applied to coastal areas, Olita et al. (2012) also developed a methodology based on hazard and vulnerability indexes determined from concentrations of oil at two different times and places and from two vulnerability factors: the beaches geomorphology and the level of protection for the areas under study. Liu et al. (2013) determined the risk of environmental pollution using a hierarchical system of indexes with four levels. The risk index was determined directly from hazard and vulnerability indexes, based on a set of sub-indexes referring the risk source state, the precautionary source control of risk, the effectiveness of precautionary progress control, the exposure levels experienced by people and ecosystems, and the local adaptive capacity to potential pollution accidents. On a more conceptual and comprehensive perspective, Santos et al. (2013) developed an operational model based on the link between marine spatial planning (MSP) and oil spill risk analysis (OSRA), by analysing the key processes and identifying commonalities between both methodologies, MSP and OSRA. These authors propose that oil spill risk analyses estimate the environmental and socio-economic values and the extent of the damage that a spill may represent to a specific area. Kleissen et al. (2007), in the context of a marine environmental risk assessment for the Dutch continental shelf, identified marine areas under high environmental risk associated with the oil transport in the North Sea, and developed methodologies and tools that allowed the assessment of oil spill and other hazardous materials environmental risk.

The qualitative methodologies, which are usually associated with the use of risk matrices, can be illustrated by the work developed by Lee and Jung (2013) on risk assessment and on a national plan for spills, accidents with oil and dangerous substances that occurred between 1994 and 2005 near Korea. In this study, the risk matrices were created based on the relation between the frequency and the severity of the accidents, which depended on the substance and spill volumes. IPIECA (2013) provided guidance and recommendations for the implementation of effective risk assessment and oil spill response planning associated with the