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Probabilistic risk assessment of oil spill from offshore oil wells in Persian Gulf

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ABSTRACT

Oil spills in the marine environment can have serious environmental, social and economic impacts. These impacts may be of transnational nature, and this makes the oil spill problem an international issue. Therefore, it is necessary to develop a common structured methodology for oil spill risk assessment. In this research, a general framework is presented for probabilistic risk assessment of oil spill from offshore oil wells. A case study is also performed in Persian Gulf to quantify the risk posed by 357 offshore wells to the near-shore receptors. First, thousands of hypothetical spill scenarios of different volumes are defined and simulated using a Lagrangian particle tracking model. Then, the result of the simulations is statistically processed to generate the risk networks and risk maps. The result of this research shed light on the importance of the pattern of environmental forcing elements and the frequency of spills in oil spill risk assessment.

1. Introduction

Over the last decades, oil spill events have contributed significantly to marine and coastal pollution (Singkran, 2013). These events have earned a special attention given that they have critical impacts on marine habitats, wildlife, fisheries and human activities (Frazão Santos et al., 2013; Mokhtari et al., 2015), especially in coastal areas (de Andrade et al., 2010; Lamine and Xiong, 2013). The first step in the process of controlling the impacts of oil spill is risk assessment. Then, the risks should be reduced through frequency reduction of spills, or improvement on spill response and resource protection strategies.

Difficulties in measuring probability of occurrence and the potential consequence of spill events, and the handling of geography make oil spill risk assessment difficult (Jolma et al., 2014). However, identification of areas of higher risk is critical for decision making (Denner et al., 2015), and considering the potential for transnational impacts of oil spills in many locations, it is necessary to define a common methodology for oil spill risk assessment (Sepp Neves et al., 2015).

The uncertainty problem has a great importance in oil spill risk assessment (Etkin et al., 2017; Sepp Neves et al., 2015) because predicting the trajectory, fate, and effects of spills depends on a large number of probabilistic variables including spill location, spill volume, weather conditions, currents, winds, and waves. To account for the uncertainty in the input variables, there is a need for probabilistic or stochastic modeling.

The integration of spatial data and oil spill simulation has significantly enhanced the effectiveness of oil spill risk assessment (Nelson et al., 2015; Frazão Santos et al., 2013; Bejarano and Mearns, 2015). This has been specifically effective in probabilistic models, in which an ensemble of hypothetical spill scenarios is simulated to derive statistical measures of the spill risk. The first models for probabilistic oil spill risk assessment have been developed from 1980s to 2000s (Guillen et al., 2004; Price et al., 2003; Smith et al., 1982).

Because of the importance of oil pollution, development of the oil spill risk assessment models has been continued, and in the recent years, various new methodologies have been presented and used in different marine environments (Al Shami et al., 2017; Alves et al., 2016, 2014; Depellegrin and Pereira, 2016; Fernández-Macho, 2016; Goldman et al., 2015; Guo, 2017; Jolma et al., 2014; Kankara et al., 2016; Landquist et al., 2016; Lee and Jung, 2015, 2013; Liu et al., 2015; Mokhtari et al., 2015; Nelson et al., 2015; Sepp Neves et al., 2015; Singkran, 2013; Valdor et al., 2016). Some software programs have been also developed for probabilistic analysis of the oil spill risk. These include TAP II™ (NOAA, 2000), OSCAR (SINTEF, 2014), and SIMAP™ (Applied Science Associates, 2017). The probabilistic models have been developed to calculate the likelihood that there will be an impact of a particular level/degree at different areas.

Oil spill risk can be defined as the combination of the probability that a particular spill event will occur and the magnitude of the consequences or impacts of that spill (Etkin et al., 2017). Sepp Neves et al.

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(2015) have presented a framework with a focus on the international risk management standard ISO 31000. In that framework, the coastline is divided into different segments, and the oil spill risk for each segment is calculated as multiplication of its sensitivity index and oiling likelihood. Different spill scenarios are simulated and the oiling likelihood for each coastal sector is calculated as the average concentration of oil in the sector divided by the average oil concentration in all coastal sectors.

In a research by Nelson et al. (2015), some hypothetical spill scenarios in different locations were simulated, and for each coastal grid cell, an oiling likelihood was calculated as the total number of oil spill parcels occurring within it divided by the total number of oil parcels that make landfall. Oiling likelihood of each cell was multiplied by its overall sensitivity index to calculate the vulnerability score of it. In another study by Depellegrin and Pereira (2016), the shoreline vulnerability score for each part of the shoreline was defined as multiplication of its sensitivity index and oil impact probability. In that research, the oil impact probability was defined based on simulation of many hypothetical spill scenarios with different start-times.

Lee and Jung (2015) used two factors for determining oil spill risk: the impact likelihood and the first impact time of the spilt oil. They simulated a number of hypothetical spill scenarios for computation of these two factors for different receptors. The oiling likelihood for a receptor area was calculated by averaging the fraction of spilt oil that reaches to the area in different scenarios. The authors believed that the first impact time of the spilt oil was an important parameter, from an emergency response point of view.

Goldman et al. (2015) defined the oil impact probability based on simulation of many hypothetical spill scenarios in different locations with different start-times. Oil impact probability for a receptor was defined as the fraction of the scenarios in which the maximum concentration in the receptor exceeded 0. They also defined a parameter, mean pollution time, to account for the residence time of the spilt oil in different receptor areas. The authors considered the residence time of the spilt oil, because they believed that the higher the residence time of the oil in an area, the higher the effects.

In a study by Al Shami et al. (2017), oil spill threat was quantified as a function of three oil pollution metrics: susceptibility of oiling (or, oiling likelihood), the average volume of oiling, and the average oil beaching time. The three metrics were derived based on simulation of an ensemble of scenarios, and an integrated index, WASH (Weighted Assessment of Shoreline Hazard), was utilised to encompass them in a single number. The WASH index of each coastal sector was then combined with its environmental sensitivity index (ESI) to derive a risk index for it. In that research, oiling likelihood for each coastal sector was calculated based on the number/frequency of hits by oil, considering the ensemble of the simulated scenarios.

Guo (2017) has developed a statistical model for probabilistic oil spill risk assessment. In that model, multiple hypothetical spill scenarios are modeled, and the risk index for each receptor cell is calculated as multiplication of five variables: oiling probability, cell area, average oil slick thickness, mean exposure duration, and sensitivity index.

In the past research, the risk of small spills has been usually ignored, although these spills may occur more frequently and pose a significant level of risk to the environment (Fraser and Racine, 2016; Sepp Neves et al., 2015). In addition, most of the developed models have ignored the aggregation of risk from different sources, while in a real marine environment, a receptor usually receives some risk from different sources, simultaneously. In the proposed framework in this research, the simulation of spills of different volumes and different frequencies has been considered. Furthermore, the total risk to each receptor is defined as aggregation of the risk posed by different sources.

2. Material and methods

2.1. Study area

Persian Gulf is a shallow semi-enclosed marginal sea that is exposed to subtropical climate (Kämpf and Sadrinasab, 2006). It is about 1000 km long and at most 350 km wide, and its mean depth is 36 m. In this gulf, the evaporation rate (~2 m/year) is considerably greater than the river runoff and precipitation (Hosseinibalam et al., 2011; Pous et al., 2015), and as a result of that, it is a negative estuary characterized by high salinities and accumulation of contaminants (Al-Rabeh et al., 1992). Persian Gulf has experienced the greatest oil spills in the world. For example, in 1980s and 1990s, significant amount of oil was released to the waters of this gulf as a result of military attacks (Al-Amirah, 1983; Al-Rabeh et al., 1992). Because of the extensive number of oil and gas exploration and production activities, oil spills have continued to occur, and in the recent years several spill events have been reported in Persian Gulf. To manage the risk of oil spill events, their risk should be quantified and understood by decision makers. Therefore, risk assessment of oil spill events is of high importance. The study area in this study covers an area of 223,043 km^2 and a shoreline length of 3124 km (See Fig. 1).

The most known weather phenomenon in Persian Gulf is the Shamal, a northwesterly wind which prevails throughout the year. Other winds are more localized and seasonal, for example, Kaus or Suhaili blowing from south, or Nashi blowing from the northeast (Pous et al., 2015). The residual sea currents in the Persian Gulf have been mainly attributed to 1) wind forcing and the Coriolis Effect, and 2) density gradients related to evaporation, radiative heat transfer, and winter inflow at the head of the gulf (Al-Rabeh et al., 1992). The tidal forcing is important for instantaneous circulation, but generates weak residual currents (Pous et al., 2015). The circulation of water in Persian Gulf has been broadly studied in the past research (Kämpf and Sadrinasab, 2006; Pous et al., 2015; Reynolds, 1993; Yao and Johns, 2010a, 2010b). Generally, there is an inverse estuarine circulation with a fresh surface inflow from Gulf of Oman and a high saline water leaving the Persian Gulf through the deep part of the Hormuz Strait (Hosseinibalam et al., 2011). The general surface current pattern in Persian Gulf is shown in Fig. 2.

The spill sources in the pilot study in this research are 357 offshore oil production wells that are all located in the northern part of Persian Gulf. These wells belong to 16 different oil fields. Since the wells of each field are close to each other, the set of the wells in each field is assumed as a point source located at the center of the field. Hence, the 357 production wells are summarized as 16 point sources of spill. These sources are tabulated in Table 1, and their locations are shown in Fig. 3.

Since coastal areas are usually more vulnerable to oiling, the focus of this study is on coastal receptors. The risk-receptor areas in this research are 20 polygons of equal lengths defined along the shoreline. The width of each polygon in the direction perpendicular to the shoreline is equal to 10 miles (see Fig. 3). The coastline under study belongs to Iran, Iraq, Kuwait, Saudi Arabia, Qatar and United Arab Emirates.

2.2. Probabilistic risk assessment

The purpose of probabilistic risk assessment is to generate a statistical result based on analysis of a representative number of possible scenarios. In the context of this research, a scenario is a specific spill event which occurs at a certain source (or, location), at a certain time, and with a certain release amount and duration. The three main steps in the proposed framework in this research are summarized in Fig. 4.

2.2.1. Generating hypothetical scenarios

The first step is defining a suitable number of spill scenarios. The defined scenarios should statistically represent all of the possible spill events in the problem under study. In this study, for each release