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Inferring spatial distribution of oil spill risks from proxies: Case study in the north of the Persian Gulf

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A B S T R A C T

Maps of oil spill probability are important tools in environmental risk assessment and decision making in coastal zone management. This paper describes the development of a spatial predictive model for the probability of oil spills in the northern part of the Persian Gulf. The model estimates the probability of oil spills at a pixel level as function of four proxies, i.e., ship routes, coastlines, oil facilities, oil wells. It uses a generalized linear model (GLM) with a polynomial function that is implemented in the R software environment. For training the model, we used reported oil spill events that represent the location of their occurrences. We trained and tested the model in 100 iterations, using a different subset of data for each. The model evaluations showed mean accuracy of 0.79% (range 0.68%–0.89%), expressed by the area under the curve (AUC). In the northern part of the Persian Gulf, the largest probability of oil spills was predicted in areas where actual oil facilities in combination with high intensity ship traffic are in evidence. The model can predict the probability of oil spills as raster map in a standard R data format. It can be used in environmental risk assessment as well as an input for more detailed oil spill simulation models. The advantages of the model include its' high spatial resolution, accounting for uncertainty in oil spill locations, and the possibility of sharing as an open-source R script with other users.
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1. Introduction

Oil spills are a serious environmental problem with critical impacts on marine and coastal habitats, wildlife, fisheries and human activities (Allan et al., 2012; Fattal et al., 2010; Carson et al., 1992). Coastal areas provide important resources for livelihood activities, fisheries, transport industries and recreation (Vafai et al., 2013; Singkran, 2013). At the same time, these areas are at risk of oil spills caused by vessel navigation, oil transport via cargo ship or submerged pipelines and by oil exploration activities (Jolma et al., 2014; Ng and Song, 2010; Kankara and Subramanian, 2007; Bigano and Sheehan, 2006). Risk of oil spill is commonly defined as a combination of an event, its consequences, and the uncertainty related to both (Aven, 2010; Burgman, 2005). An environmental risk assessment must have the capacity to support decision making for preventing future oil spill disasters as well as to develop optimal planning and management strategies in response to oil spill events. This requires identifying and prioritizing areas in the coastal zone where there is a need for an allocation of resources, while minimizing the risks and costs (Keeney, 1982; Mata and Corchado, 2009). For large marine areas, oil exploration activities are not uniform in space, therefore, a spatially distributed oil spill risk assessment is required (Burgman, 2005).

Many studies develop methods and tools for identifying and mapping potential oil spill sites and supporting oil spill risk management (Ko and Chang, 2010; Lehikoinen et al., 2012; Jolma et al., 2014; Juntunen et al., 2005). A very large number of studies have been conducted to model and predict the impact of major oil spill

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accidents, for example of the Exon Valdez accident (Carson et al., 2003; Wiens and Parker, 1995), BP Gulf of Mexico oil spill (Sammarco et al., 2013; Allan et al., 2012), Prestige accident (Bernabeu et al., 2013; Díaz et al., 2008), Braer oil spill (Spaulding et al., 1994), and Gulf War (Bejarano and Michel, 2010; Alam, 1993). More than a thousand research articles and studies can be found about these catastrophic oil spills. However, the small, but more frequently occurring events of routine shipping operations also affect the coastal and marine environment, and should also be included in the environmental risk assessment (Ng and Song, 2010). Several authors attempted to detect the spatial distribution of oil spills by remote sensing observations (Fingas and Brown, 2014; O'Hara et al., 2013; Serra-Sogas et al., 2008) or calculate the probability of ship collision accidents (Bigano and Sheehan, 2006; van Dorp and Merrick, 2011). Density of the events was also used to visualize the oil spill incident frequency as a map (Lu, 2003). Most of these studies relied only on the reported oil spill events, but exploring the causal relationship is also important in order to understand and quantify what and to what extent different factors influence the risk of oil spills. Relying only on the reported events may not fully represent the potential risk, as it is likely that some events are not reported, or their measurements are subject to error and uncertainty (Fingas and Brown, 2014; O'Hara et al., 2013). Exploring the association between the factors that may cause an event (causal factors) and the data on oil spills can lead to construction of a model that can be used to predict the spatial distribution of potential risks of an oil spill over the whole study area. If a significant relationship between the factors and the events is found, the factors (explanatory variables) can be used as proxies to predict the spatial distribution of the events. Such methods have been used in many disciplines where observations are scarce, for example, in species distribution (Naimi et al., 2014) or air pollution source modeling (Hoek et al., 2008). The spatial distribution of the probabilities for an oil spill occurrence has been generated based on simulation of oil spill trajectories and used in an oil spill risk analysis (Price et al., 2003). The importance of including causal factors (e.g., ship route proximity) in mapping operational oil discharges has been highlighted by Serra-Sogas et al. (2014). Liu et al. (2015) modeled the spatial risk of oil spill in China's Bohai Sea using the ships and platforms as potential oil spill locations. Locations with high probability of oil spill in the Gulf of Finland were identified by Jolma et al. (2014) using the Bayesian network method. Moreover, Hong et al. (2010) developed a model for estimating the probability of oil spill in the Luoyuan Bay in China using the ship traffic intensity as an explanatory variable. Singkran (2013) identified zones in the coastal waters of Thailand by classifying impacts of oil spills using explanatory variables such as the number of ports and boats.

Although most of the above mentioned studies have focused on modeling the fate of oil spills either for simulating a big event after an accident, or for assessing the oil spill vulnerability in coastal areas, there is still a need to predict spatial distribution of such events and the probability of potential future events. Moreover, exploring and mapping the spatial distribution of potential oil spills is the first step in locating priority areas at high risk of oil spill (Liu et al., 2015). In the other words, we need to know the locations where oil spill events are most likely to occur. Defining the vulnerability of the marine environment (Garcia et al., 2013) can lead to the locations that are at high risk of oil spills, i.e. those with high probability and vulnerability. The main objective of this study was to investigate the factors that may explain the occurrence of oil spills. By linking the causal factors with the oil spill events, we developed a spatial predictive model to generate a probability map of oil spill risks in the Persian Gulf. Our study concerns a high-risk area for oil spills, due to its location where intense oil exploration activities and heavy ship traffic are in evidence. Furthermore, the International Marine Organization (IMO) has declared the Persian Gulf as Special Area, requiring the adoption of special mandatory methods for the prevention of sea pollution by oil and/or garbage (Mahmoudi, 1997).

2. Materials and methods

2.1. Study area

The Persian Gulf, a shallow and semi-enclosed basin in a typically arid climate, is located in the southwest of the Asian continent between 48° and 57° E longitude 24°–30° N latitude (Fig. 1). It is connected to the deep Sea of Oman through the narrow Strait of Hormuz. The Persian Gulf covers an area of approximately 226,000 km^2, more than 990 km in length, its width varying between 56 km (Strait of Hormuz) to 338 km. The basin has an average depth of about 35 m, the deepest water approximately at 107 m (Kämpf and Sadrinasab, 2005). The circulation in the Persian Gulf is driven by wind-stress, surface buoyancy fluxes, fresh water runoff, water exchange through the Strait of Hormuz, and tides (Hassanzadeh et al., 2011; Pous et al., 2015). In this study, we focused on the northern part of the Persian Gulf defined approximately by the Exclusive Economic Zone (EEZ) of I.R.Iran, and based on the availability of data on oil spill events.

By volume of oil transit, the Strait of Hormuz is one of the world's most strategic chokepoints. The volume of crude oil and petroleum products transported through the Strait was 15.7–17.5 million barrels per day during 2007–2011 (Rahmanpoor et al., 2014). A combination of factors, including tanker traffic, accidental spills, industrialization, port areas and refineries may directly or indirectly affects increasing of the pollution risk in the marine environment of the Persian Gulf (Sheppard et al., 2010). During the year 2012, most of the oil pollution were from the oilfield leakages with tremendous amounts of heavy oil. It has been noticed that most of the oil spills in the northern and southern parts of the Persian Gulf is from the oilfields and the shipping traffics, respectively. Besides, a very serious incident took place in the middle part of the Persian Gulf (MEMAC, 2012). Although the frequency of big oil spill incidents has decreased, the chronic oil spills from ballast water washing and from oil platform activities remain widespread that make a critical concern in integrated coastal zone management (Ebrahimi-Sirizi and Riyahi-Bakhtiyari, 2013; Mirvakili et al., 2013).

2.2. Modeling oil spill risk

2.2.1. Oil spill events

The oil spill events in the Persian Gulf were reported by MEMAC (Marine Emergency Mutual Aid Center) in the time period 2010–2013 (near 250 events). Many of the reported events are based on satellite observations and some are local reports of the northern part of the Persian Gulf. In this research, we considered the following information: latitude, longitude, and occurrence of events. To be able to fit the model, our response variable needs to follow a binomial distribution (i.e., data on locations where the oil spill events have occurred as well as those where the events have not occurred). However, our data include only the occurrence (presence) of the events. A common approach to overcome this problem is to generate the absence sites, called pseudo-absences (Hengl et al., 2009; Chefaoui and Lobo, 2008). We selected the number of pseudo-absences equal to the number of presence locations, as recommended by Hengl et al. (2009). The pseudo-absence locations were generated as random spatial samples of the study area. Based on the random choice of the locations, many

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