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Research article

Towards a common oil spill risk assessment framework – Adapting ISO 31000 and addressing uncertainties

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ABSTRACT

Oil spills are a transnational problem, and establishing a common standard methodology for Oil Spill Risk Assessments (OSRAs) is thus paramount in order to protect marine environments and coastal communities. In this study we firstly identified the strengths and weaknesses of the OSRAs carried out in various parts of the globe. We then searched for a generic and recognized standard, i.e. ISO 31000, in order to design a method to perform OSRAs in a scientific and standard way. The new framework was tested for the Lebanon oil spill that occurred in 2006 employing ensemble oil spill modeling to quantify the risks and uncertainties due to unknown spill characteristics. The application of the framework generated valuable visual instruments for the transparent communication of the risks, replacing the use of risk tolerance levels, and thus highlighting the priority areas to protect in case of an oil spill.

1. Introduction

According to the Oil Tanker Statistics published by the International Tanker Owners Pollution Federation (ITOPF) (ITOPF, 2013), the number of oil spills in the sea and the volume of oil added to the marine environment has decreased over the last 44 years. However, there are still uncertainties regarding the origin of these spills. Vessel-related oil pollution is usually grouped into accidental or operational events. Accidental oil spills are associated with maritime casualties, e.g. grounding or collision, ranging from small (less than 7 tons) to very high volumes (it is claimed that 63,000 tons of oil were spilled during the Prestige crisis). Operational events are small, but frequent, intentional or inadvertent spillages in the sea due to ship operations (e.g. tank washing). Accidental oil spills and their impacts have been addressed by several studies (Grigalunas et al., 1986; Loureiro et al., 2009; Kingston, 2002; Schmidt-Etkin, 2011), however, little attention has been paid to operational events. The Committee on Oil in the Sea of the US National Research Council (US National Research Council, 2009) estimates that 270,000 tonnes per year are discharged due to ship operations, corresponding to 21% of the total volume of oil spilled into the sea including natural and land-based sources. The operational share reaches 51% if natural and land-based sources are not considered.

Ship-borne transportation and the size of tankers have been increasing and this trend is likely to persist (O'Rourke and Connolly, 2003). Accordingly, oil spills will continue to represent an environmental threat to marine and coastal areas. At present, there is no commonly accepted method to assess the environmental impacts of oil spills, and Oil Spill Risk Assessments (OSRAs) need to be scientifically and operationally tested.

Literature has demonstrated that oil spills are usually a transnational problem (e.g. Coppini et al. (2011); Höfer (2003)) which makes the reporting and the response to oil pollution an international contingency regulation problem (Lyons, 2012). This concern is of political importance and the European Directive on the Safety of Offshore Oil and Gas Operations recommends that the activity should follow international regulations on environmental impact assessments since accidents in one Member State may impact on

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other Member States, thus stressing the importance of risk assessments on the decision-making process (European Commission, 2013). In order to improve the preparedness for oil spill accidents and operational releases at an international level, it is necessary to define a common methodology for an OSRA.

Some key points need to be addressed by a general oil spill risk-mapping methodology. It should be based on a solid theoretical basis, which must be robust and generic enough to be replicated in different coastal environments and hazard scenarios. Finally it should rely on easy-to-access datasets, unlike previous attempts which relied on expensive and site-specific accident statistics and environmental data. In 2009, the International Standardization Organization (ISO) published the ISO 31000 defining principles and guidelines for risk management (International Standardization Organization, 2009). The standard was developed with the contribution of experts from different backgrounds (Purdy, 2010) providing guidelines for risk management in any field with the aim of furnishing a common basis to tackle the lack of standards. Given the robustness of the ISO approach and its wide acceptance, we believe the adoption of the ISO as the backbone and guideline of an OSRA framework is the first step towards a standard methodology. Thus in our study we developed an ISO compliant OSRA framework and applied it to the Lebanon oil spill crisis occurred in 2006, showing the potential of the new methodology.

The paper is organized as follows. In Section 2 we review and classify existing OSRA papers using the Landquist et al. (2013) items. In Section 3, we map the ISO 31000 standard to OSRA principles and propose a new framework. In Section 4 we carry out a case study. Finally, the discussion and conclusions are presented in Section 5.

2. Reviewing the present OSRA literature

Six fundamental papers were chosen as examples of risk mapping methodologies. The report drafted by the Queensland Transport in association with the Great Barrier Reef Marine Park Authority (QT&GBRMA, 2000), hereafter *A*, was the first to implement a standard for an oil spill risk assessment. The Risk of Vessel Accidents and Spills in the Aleutian Islands (Transportation Research Board, 2008), *B*, is the compilation of guidelines and insights for a future risk assessment in the archipelago. Two studies, Olita et al. (2012), hereafter *C*, and BOEM (2012) (in association with Price et al. (2003, 2004)), *D*, were included because of their innovative methods to compute the oil spill hazard. Transport Canada (2007), *E*, provides an innovative approach for a quantitative estimation of risk. Martini and Patruno (2005), *F*, was included for an OSRA in the Eastern Mediterranean Sea, one of the busiest maritime routes worldwide. The list of papers and their corresponding letters are presented in Table 1.

The papers were analyzed using the methodology proposed by Landquist et al. (2013). The first step consists of listing the items to be included in the Risk Assessment, namely *Establishing the Context*, *Risk Identification*, *Risk Analysis* and *Risk Evaluation* according to ISO 31000. Each item is subdivided into elements, as described in Fig. 1.

Table 1
Reviewed documents and their corresponding letters.

Paper	Corresponding letter
QT&GBRMA (2000)	A
Transportation Research Board (2008)	B
Olita et al. (2012)	C
BOEM (2012)	D
Transport Canada (2007)	E
Martini and Patruno (2005)	F

In total, twenty one elements and sub-elements were searched for in each reviewed paper, and a final mark was attributed based on the percentage of elements considered. The results obtained are shown in Table 2.

By far the most complete methodologies were those proposed in documents *A*, *B* and *E*, considering more than 75% of the parameters listed by Landquist et al. (2013). *C* and *D* scored intermediately followed by F which fulfilled only 38% of the required items.

The link between maritime accidents and oil spills is clear which was covered by all the documents reviewed. However, the majority (*C*,*D*,*E* and *F*) did not consider the different accident types separately together with their respective consequences. *A* implicitly regarded the difference between accidents by narrowing the analysis to collision and grounding accidents. Initially focused on shipwreck risks, Landquist et al. (2013) included an item addressing the ship size. Half of the studies (*A*, *D* and *E*) did not take variations in ship size into consideration.

A dichotomy was observed in the papers regarding the estimation of the oil spill hazard. *A*, *B* and *E* fully relied on accident frequencies based on both global and local databases. *C* and *D* heavily relied on simulations of oil spill trajectories, estimating hazards based on the probabilities of a given spill in a given spot reaching the coastline. *F* did not clearly describe how the oil spill hazard was defined.

All the papers clarified the sources of risk. *A*,*B* and *E* considered both bunker and cargo oil as a potential hazard. *E* only took into account crude oil transported by tankers, while *D* also included fixed platforms and pipelines. None of the reviewed OSRAs included operational oil spills as a potential source of risk.

There was considerable variety in the methodologies used to estimate consequences during the *Risk Analysis* process. *A*, *B*, *D* and *E*, at first glance, all considered the environmental, social and economic impacts of oil spills. However, *A* estimated the severity of the consequences with three vulnerability levels by integrating the three areas. On the other hand, *E* performed two separate analyses: one socioeconomic and one environmental. The OSRA *D* adopted a "binary" approach, in which a given coastal sector can be considered as important or not. Finally, *C* only considered coastal vulnerability with respect to two indicators: coastal geomorphology and protection level. In spite of the evident differences in consequences between big and small spills, only *B*, *D* and *E* used spill size as a factor affecting the consequences.

E adopted a quantitative approach to estimate the risk, computing the socioeconomic consequences using the concept of "statistical losses" and the environmental component in terms of estimated mortality rates for key bird species. *C* used a semi-quantitative approach, combining probabilities of oil reaching the coast with vulnerability indicators in order to generate a risk index ranging from 0 to 1. No comments were presented in terms of weighting indicators. Conversely, *A* opted for a qualitative approach using a risk matrix with three levels of likelihood and three levels of impacts. Finally, B proposes a two-phased strategy in which first a semi-quantitative approach is employed for the identification of the main sources of risk, which are further quantitatively estimated in the following phase. Despite using the "binary" approach to estimate impacts, *D*, did not present the methodology applied to estimate risk levels. F did not cover this topic.

Risk assessments should include an appraisal of uncertainties. Among the reviewed papers, only *A*,*B*,*D* and *E* considered uncertainties in their analyses. *A* tackled uncertainties using a conservative approach in the definition of the risk index. *E* identified the estimation of accident frequencies as the main source of uncertainties. *D* performed thousands of oil spill simulations, addressing uncertainties in meteo-oceanographic conditions, however it was limited to the hazard component of the risk

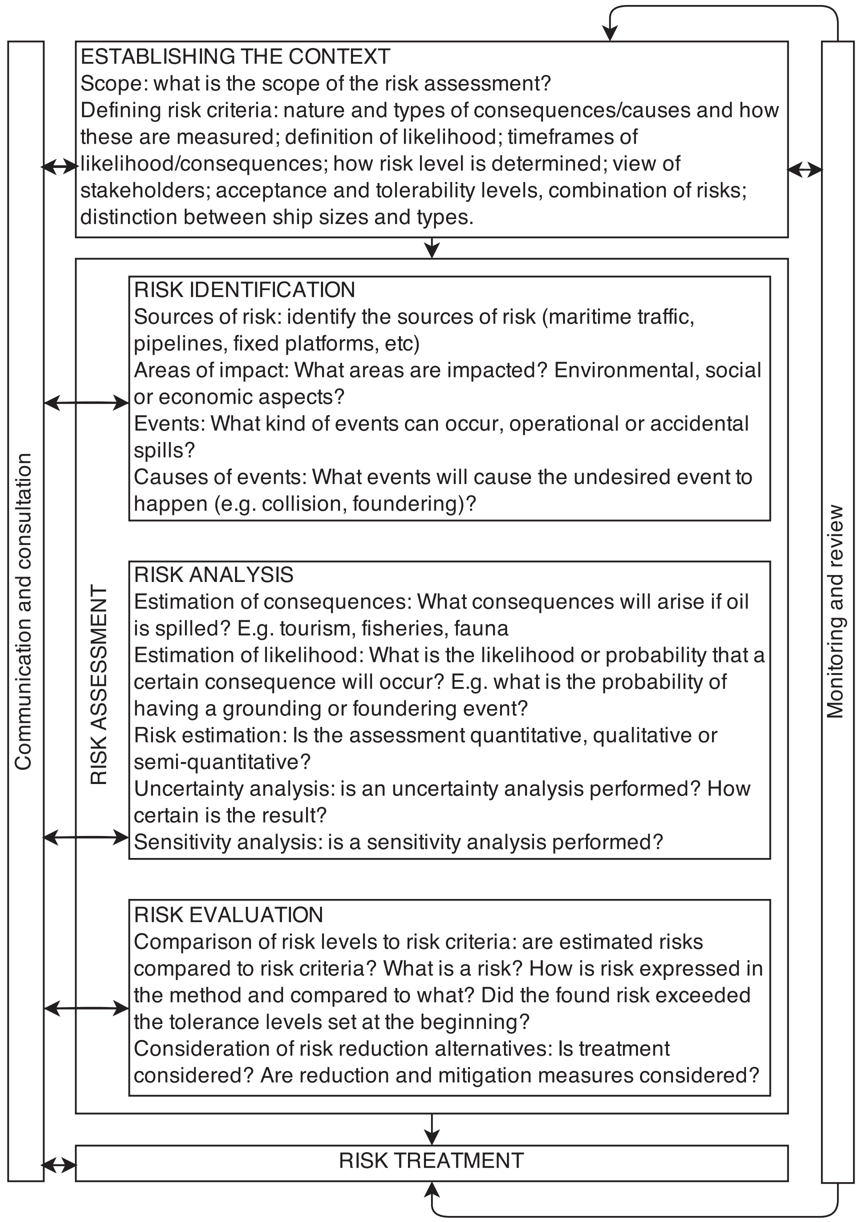


Fig. 1. ISO-based risk management framework from Landquist et al. (2013) adapted to OSRA. Items are in capital letters inside the horizontal boxes with their respective elements in lower case.

equation. In general, no OSRA paper carried out a proper combined analysis of uncertainties in the hazard and vulnerability components of the risk assessment problem.

3. Adapting the ISO 31000 to oil spill risk assessments

The ISO standard was designed to be applied to a wide range of topics. Therefore, mapping it to the topic of interest prior to its application is of primary importance. The methodology proposed by Landquist et al. (2013) is suitable for shipwrecks but oversimplified for cases in which maritime traffic and oil production are both likely sources of oil spills. The International Oil and Gas Producers Association (OGP) also developed an ISO-compliant framework to give support to offshore oil production companies, aimed

Table 2
Reviewed documents and their respective scores.

Landquist et al. (2013) items	Paper A (%)	Paper B (%)	Paper C (%)	Paper D (%)	Paper E (%)	Paper F (%)
Establishing the context	90	100	60	60	70	50
Risk identification	100	100	50	75	75	50
Risk analysis	80	80	60	80	80	0
Risk evaluation	100	100	0	0	50	50
Overall score	90	95	57	62	76	38

at exploration/production facilities from an operator perspective. In this section, the ISO items are interpreted as OSRA items and compared to what has been previously proposed by Landquist et al. (2013) and the OGP. The results are summarized in the Supplementary Material (Table S1).

In the *Establishing the Context* ISO step of Table S1, objectives, scope, strategies, responsibilities and accountabilities should be stated, followed by a description of the criteria used to define risk and the methodology employed to estimate it. In the OSRA case, the first step should be to define the character of the analysis (qualitative, quantitative or a combination), limit the geographical area and define the specific hazards and impacts to be considered. It should also contain the relevant legislative regulations related to oil pollution and environmental quality standards. Institutions working on oil spill reporting, such as the European Maritime Safety Agency (EMSA), and response (e.g. Coast Guard) should be identified and taken into consideration. Clearly, the actual needs of the institution implementing the risk management should also be stated.

OGP and Landquist et al. (2013) failed to carry out a comprehensive review of the legislation on environmental standards and oil pollution, and of the interactions among institutions. For example, environmental standards are mainly regulated by the Marine Strategy Framework Directive (MSFD) in the context of the European Union, which requires the establishment of environmental targets and the implementation of monitoring indicators. In this way, the MSFD is expected to impact, for instance, the way oil spill consequences are estimated and the indicators adopted for risk monitoring. Where a risk tolerance level is proposed, it should take into account the general guidelines and the standards of good environmental status proposed by the Directive. Based on the ISO guidelines, elements regarding the "*International and domestic legislation on oil spill pollution*" (Element 1 in Table S1. Hereinafter only numbers will be presented.), "*Governance, roles and accountabilities on oil spill prevention, detection and combat*" (4) and "*Environmental standards, policies and objectives to be achieved*" (5) were included in our framework.

Trends in both hazards (e.g. increase in maritime traffic or oil production) and impacts (e.g. increase in population in coastal areas or in the share of the sea related economy) were addressed in our framework through the element "*Drivers and trends impacting oil spill hazard*" (2). OGP and Landquist et al. (2013) did not consider long-term variations in oil spill risks and OGP did not address the possible combination of risks.

One of the recommendations of ISO 31000, followed by Landquist et al. (2013) and OGP, is the definition of risk tolerance levels during the establishment of the context. This may not be applicable for OSRAs (Fischhoff (1995), Aven and Pitblado (1998), Aven and Kõrte (2003), Aven and Vinnem (2005)) and was disregarded in our framework. The element "*Risk tolerance criteria*" (25) was thus removed.

Establishing the Context is followed by a *Risk Identification* step (Table S1). According to ISO 31000, the organization must "*identify sources of risk, areas of impacts, events (including changes in circumstances) and their causes, and their potential consequences*". When mapping it to OSRA, it is important to bear in mind that both operational and accidental oil spills represent hazards to the marine environment. The decision to address one or both risk sources will depend on the scope of the OSRA, however, to assume negligible impacts of operational oil spills in the environment is a mistake. In agreement with Landquist et al. (2013), the element *Events* was rewritten as "*Pollution events considered - operational and/or accidental spills*" (30), given the growing awareness on the role operational discharges of oil play on marine pollution. The OGP framework does not take operational pollution events into consideration.

Variations in the oil spill risk have been identified by previous studies as being due to, for instance, sea conditions (Eide et al., 2007; Balmat et al., 2009), and maritime traffic distributions (Olita et al., 2012). In our framework, the risk was considered as a dynamic index, in which short-term spatial and temporal variations were tackled including the element "*Variables modulating the oil spill hazard and impacts and how they will be measured*" (28), which may include, for instance, changes in meteo-oceanographic conditions and their respective impacts on oil trajectories and accident probabilities, or seasonality in maritime traffic.

Studies such as Grigalunas et al. (1986), O'Rourke and Connolly (2003), McCay et al. (2004) and García Negro et al. (2007) determined the multiple impacts associated with the oil industry. They demonstrate that impacts are not restricted to the biota, but also include the economy and society. Thus, coastal vulnerability should be considered as a composite index, covering environmental, social and economic aspects, as recommended in item (29). This is a common practice in OSRA, however some analysts still neglect it. A description of the process behind the construction of the vulnerability index is rarely presented. It is advisable that the inclusion/exclusion of variables in an index and their respective weighting should represent the priorities of the local stakeholders.

Once risks are identified, a *Risk Analysis* process must be undertaken, where the identified risks are quantified. Firstly, operational and accidental oil spills should be treated separately since the former can be considered as a high frequency/low impact hazard, while the latter is characterized by low probabilities/high impacts. This approach is recommended by the ISO and by the Organisation for Economic Co-operation and Development (Organisation for Economic Co-operation and Development, 2008) and prevents the inappropriate combination of the two components in the risk analysis.

Assessments of uncertainties should play a major role in the *Risk Analysis* and, in accordance with ISO 31000, we added them to the OSRA framework (36). Concerning marine OSRA, oil spill characteristics (e.g. oil type, moment of spillage, spill rate, spilled volume) and meteo-oceanographic conditions affect the oil trajectory and, therefore, the coastal segments impacted. It is difficult to get precise oil spill characteristics either for accidental or operational events, and meteo-oceanographic fields have large uncertainties especially for long-term forecast, thus making those two components the dominant sources of uncertainty in OSRA. An innovative method to address uncertainties will be part of the *Risk Analysis* step in the Lebanon case study that will follow.

Assuming the *Risk Identification* process has considered oil spill risks as significantly variable in the area of interest, this should be quantified. Although seldom considered, existing controls (e.g. early warning systems, response plans, etc) should be taken into consideration. Therefore, the item "*Effectiveness and efficiency of the available oil spill prevention, detection and combat instruments*" (34) was included in our OSRA framework, complementing the "*Identify potential preventive measures*" proposed by the OGP. Landquist et al. (2013) does not consider control measures.

The final step recommended by ISO 31000 is to undertake a *Risk Evaluation process*. It is argued that risks estimated during the *Risk Analysis* step should be compared to the previously defined tolerance levels in the *Establishing the Context* step, thereby identifying and prioritizing those that actually need treatment. We propose replacing it by the development of *Risk communication tools and information dissemination* (39) to inform the *Risk Analysis* outputs, expressing risk magnitude, spatial-temporal variations of risk, uncertainties and risk interactions, and comparing alternatives (Lipkus and Hollands, 1999). In addition, we removed the element "*Identifying risks that need treatment*" (40) proposed by the ISO 31000 on the basis that any risk should be kept as low as reasonably practicable.

In conclusion, Table S1 contains the 35 final elements of the

Table 3
OSRA framework applied to the Lebanon crisis, 2006.

Establishing the context		
1	International and domestic legislation on oil spill pollution	International agreements signed by the Lebanese government: Barcelona Convention, Emergency Protocol ′76, MARPOL, CLC ′69 (Martini and Patruno, 2005). Domestic regulation: Law on the Protection of Environment 444/02 (Massoud et al., 2012).
2	Drivers and trends impacting oil spill hazard	The energy policy scenario in Lebanon was described by Houri (2006) as an increasing share of oil-related energy production, depicting a positive trend in the oil spill hazard. By July, 2006, the hostilities with Israel were growing, modulating the main driver (for the present assessment) of the oil spill hazard.
3	Perceptions of stakeholders regarding the oil hazard	Djoundourian (2009) states that the environmental awareness of the Lebanese society was little before the Jiyeh event and going through a downward trend.
4	Governance, roles and accountabilities on oil spill prevention, detection and combat	Ministry of the Environment (government)/Directorate General for Ports and Port Authorities (operational responsibility).
5	Environmental standards, policies and objectives to be achieved	Law 690/2005 entrusts the Ministry of Environment as the institution responsible for setting the environmental standards (METAP – World Bank, 2009). By the time of the accident, no standard had been proposed (Climate Policy Watcher, 2014).
6	Capabilities on oil spill prevention, detection and combat	Government and private response equipment to tackle minor oil spillages (Martini and Patruno, 2005).
7	Oil spill contingency plan	By 2006 Lebanon had no National Contingency Plan (Martini and Patruno, 2005). Neighboring countries (i.e. Egypt, Israel and Cyprus) developed an international contingency plan within the Barcelona Convention.
8	Standards, guidelines and models adopted by the organization	The Lebanon Government requested through REMPEC oil spill modeling predictions but the Lebanese Government was not yet organized to use such information as a risk reduction policy in case of oil spills.
9	Goal and objectives of the oil spill risk management	To improve the environmental status of the marine and coastal areas surrounding the Jiyeh power station.
10	Responsibilities in the risk management process	Jiyeh power station.
11	Scope and depth of the OSRA, including specific inclusions and exclusions	To evaluate a posteriori the probability of oil beaching due to a single source of risk: the shelling of an oil storage unit at the Jiyeh power station.
12	Geographical coverage and life span of the OSRA	Lebanese coast during the month of July 2006
13	Establish methods, models and tools	Ensemble oil spill simulations will be combined with a coastal vulnerability index map
14	Define the way performance and effectiveness are evaluated in the management of risk	e.g. accident simulations, risk acceptance by the local community.
Establishing the context		
15	Identifying information/instruments needed for a better risk management	The World Bank (2007) identified that, in addition to the engagement of the stakeholders, valid information about tourism, biodiversity and fisheries was lacking prior to the Jiyeh oil spill, thus compromising the ecosystem management.
16	Accident types, their causes and consequences and how they will be measured	Complete rupture of an oil storage unit due to explosion resulting in a catastrophic spill.
17	How likelihood will be defined	Likelihood is defined as the probability of the oil reaching the coast based on oil spill simulations.
18	How the level of risk is determined	Quantitatively.
19	Time frame of the likelihood and consequences	Valid for July 2006. Longer ensemble simulation should be carried out for longer time frame.
20	View of the stakeholders regarding hazards, impacts and risk determination method	Not applicable for the case study. Such analysis should have been undertaken prior to the accident since an accident in the past may change the view of the stakeholders.
21	Combination with other risks and how this will be considered	Assumed as negligible for the case study.
Risk identification		
22	Potential sources of oil pollution	Jiyeh oil storage units.
23	Variables affecting the oil spill hazard/impacts and how they will be measured	Variations in meteo-oceanographic conditions and oil spill characteristics (volume, spill rate and type of oil) and their respective impacts on the oil spill hazard will be measured through ensemble oil spill simulations.
24	Areas of impacts (environmental, social and economic)	Cultural and ecological aspects proposed by UNEP – ROWA (2012).
25	Pollution events considered	Accidental oil spill.
26	Causes of events	Intentional attack on the oil storage unit.
Risk analysis		
27	Estimated environmental, social and economic impacts in the area	From our analysis, 9 out 15 of the high priority and 13 out the 20 medium priority coastal sites were impacted by the spill with different volumes (Fig. 3a) and uncertainties (Fig. 3b).
28	Likelihood of actually polluting vulnerable areas	Presented in Fig. 4a
29		

Table 3 (*continued*)

	Effectiveness and efficiency of the available oil spill prevention, detection and combat instruments.	Spill detection system unavailable and combat instruments unable to tackle large spills.
30	How risk levels are estimated and expressed	Risk levels are calculated in a quantitative manner through Equation (1) and expressed in relative levels between 0 and 1.
31	Uncertainty analysis	Sources of uncertainty are: meteo-oceanographic inputs for the oil spill model, oil spill model setup as volume of oil spilled, time of spillage and duration of the spill (Fig. 4b).
32	Sensitivity analysis	The ensemble simulation demonstrated that among the evaluated variables (i.e. oil type, spilled volume, spill time and duration of the spill) the duration of the spill and oil type were the main variables controlling the distribution of oil on the coast (Supplementary material, Figs. S2 and S3).
Risk evaluation		
33	Risk communication tools and information dissemination	Visual representation of cultural-ecological priority sites (Supplementary material, Fig. S1), modeled oil spill beaching (Fig. 3a) and its variability (Fig. 3b), probability of coastal contact (Fig. 4a), total risk (Fig. 6) and its uncertainties (Fig. 4b).
34	Prioritization for risk treatment	Priority areas for treatment are defined based on Fig. 6.
35	Consideration of risk reduction alternatives	According to the International Convention on Oil Pollution Preparedness, Response and Cooperation (International Maritime Organization, 1990), some key points should be covered in order to reduce the risk: (1) local oil pollution emergency plan, (2) oil spill reporting system, (3) definition of national/regional competent authorities, (4) national contingency plan, (5) minimum response equipment available and (6) international cooperation.

OSRA for accidental and operational oil spills. In the next section this methodology is applied to the Lebanon case study.

4. The OSRA case study: 2006 Lebanon crisis

Between the 14th and 15th of July, 2006, two oil depots of the Jiyeh power station, located in Lebanon, were shelled during the Israel–Lebanon hostilities, spilling between 10,000 and 20,000 tonnes of oil. The OSRA framework proposed in Section 3 was applied to the Lebanon oil spill crisis and the results are presented in Table 3. The assumptions made for each of its elements are described below.

It is clear that our case study covered only one source of risk, i.e. a power plant explosion, and that an OSRA should be carried out for many other sources of risk, however this is outside the scope of this case study.

4.1. Establishing the Context

The main goal of the OSRA was to improve the environmental status of the marine and coastal areas surrounding the Jiyeh power station regarding accidental oil pollution (element 9 in Table 3. Hereinafter only element numbers will be presented). The Jiyeh power station was the only source of risk addressed and therefore, for the purposes of our case study, it was considered as the main entity responsible for the risk management (10). Secondly, only one type of event was considered: the intentional explosion of the oil storage units (11, 16, 21).

Although Lebanon is a signatory of international agreements on marine oil spill control (1), the country had no national contingency plan when the spill occurred (7), no related standards/guidelines/models (8) and only limited capacity to respond to large-scale oil spills (6). The implementation of domestic environmental legislation was still ongoing (5), designating the Ministry of the Environment as the reference point at the governmental level regarding oil spills, and the Directorate General for Ports and Port Authorities at the operational level (4). Environmental awareness of the stakeholders was limited (3). Two main drivers contributed to an overall increase in the oil spill risks: hostilities with Israel were growing and the energy policy in Lebanon was moving towards increasing oil-derived energy production (2).

The geographical coverage of the OSRA should not be restricted to Lebanese waters. Satellite images analyzed by Coppini et al. (2011) during the crisis and the UNEP-Regional Office for West Asia report (UNEP - ROWA, 2012) showed that parcels of oil also reached the Syrian coast transported by currents and waves. However, in order to keep the analysis concise, the risk assessment was limited to the Lebanese coast (12).

The likelihood was estimated through oil spill simulations (17), which were later combined with coastal vulnerability data to produce the quantitative risk scenario for a catastrophic spill (13, 18). The time frame of the assessment was restricted to July 2006 due to the inputs used to run the oil spill simulations (19).

According to the report devised by the World Bank (2007), more information on tourism, biodiversity and fisheries was necessary to better estimate the impacts of the Jiyeh oil spill (15). The report also highlighted the importance of stakeholder involvement for a better risk management (15, 20). Finally, the effectiveness of the OSRA could be improved, for example, via accident simulations and risk acceptance surveys, although public participation in defining performance indicators is paramount (14).

4.2. Risk identification

As previously discussed, the only potential source of risk in the OSRA was the power station oil storage facilities (22). Thus changes in risk were modulated by changes in meteo-oceanographic conditions and characteristics of the oil spill (23). After the crisis in 2006, the UNEP – ROWA (2012) identified fifteen high priority and twenty medium priority sites in terms of ecological and cultural aspects (Supplementary material, Fig. S1) (24). Unfortunately, the report does not include accurate estimates of the socioeconomic aspects of the coastal sites. Events triggering oil pollution were restricted to an accidental oil spill (25) caused by

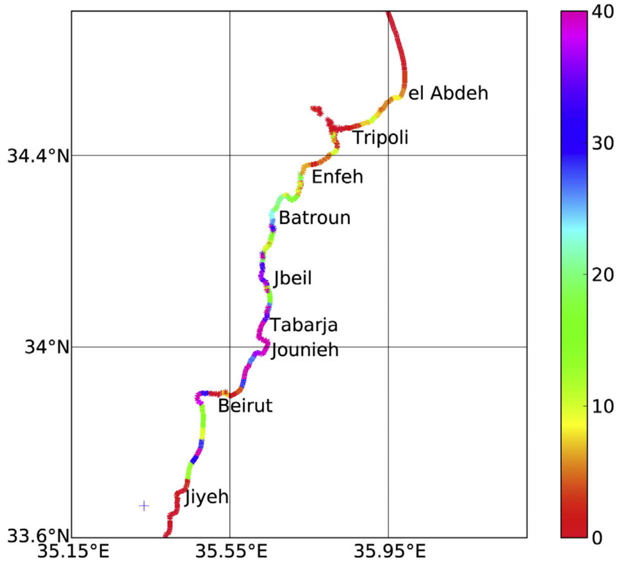


Fig. 2. Beached oil for the 10/08/2006 – 06:00 estimated with the reference simulation based on Coppini et al. (2011) (tonnes/km). Blues cross in this and in the following figures represents the initial position of the spill. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the explosion of an oil depot (26).

4.3. Risk analysis

From a quantitative perspective, the risk was estimated for each coastal sector n of the Lebanese coast using the following equation:

$$R_n = (P_{cc})_n \cdot I_n \tag{1}$$

where $(P_{cc})_n$ is the probability of oil beaching for the segment n and I_n are the impacts (30). I was defined for each coastal segment by adopting a vulnerability index with a value of 1 for high priority sites, 0.5 for medium priority, and 0.25 for undefined areas. Since no prevention, detection and combat instruments were identified, no controls were applied to the risk equation (29).

The ability of oil spill modeling to generate reliable predictions of the trajectory of a spill and impacted coastal segments have been successfully demonstrated by, for instance, Abascal et al. (2010) for the Prestige accident off the Spanish coast and Coppini et al. (2011) for the Jiyeh event. Errors related to the oil spill model were discussed at length by Coppini et al. (2011) and Lardner et al. (2006) with the conclusion that precise knowledge of the initial spilling event and high resolution currents were essential to reduce uncertainties. In addition, Samaras et al. (2014) demonstrated the impact of uncertainties due to the definition of coastal types and in the beaching algorithm. Information on the volume spilled, spill rate and type of oil also diverged significantly, adding uncertainty to the model parameters.

Ensemble oil spill simulations were used to calculate P_{cc} and its uncertainties. A reference simulation was performed using the best model setup tested by Coppini et al. (2011), forced by SKIRON high resolution winds (Kallos et al., 1997) and CYCOFOS high resolution currents (Zodiatis et al., 2006, 2008) (Fig. 2). Together with the reference simulation, eight other runs were carried out, changing one single variable at a time, covering the different information on the oil spill characteristics identified in the literature (Table 4). All the experiments were performed using the latest version of MEDSLIK-II oil spill model (De Dominicis et al., 2013), including the developments proposed by Samaras et al. (2014). The results are presented in the Supplementary material, Figs. S2 and S3. In order to remove spurious small scale variability in the beached oil volumes, the coastal segments were aggregated into 2 km long sectors.

Comparisons among ensemble members and to the reference simulation, shown in Fig. 2, suggest that the output was particularly sensitive to the duration of the spill, as demonstrated by members 7 and 8. Both show smaller or absent oil beaching south of 33.8° N and the shorter duration of member 7 restricted the area of high oil concentration (>20 tonnes/km) between the Beirut peninsula and Jbeil. Increased oil density in member 1 resulted in higher concentrations of oil on the coast for the whole domain. A lower volume of spilled oil led to lower concentrations on the coast, as demonstrated by member 3. Differences in the moment of spillage did not affect the final scenario as much as the other variables (32).

Fig. 3 presents the ensemble mean concentration of oil on the coast and its standard deviation. In total, 9 out 15 of the high priority sites and 13 out 20 of the medium priority sites were impacted by the spill with different volumes and uncertainty. The most affected areas were the Beirut peninsula and the coastal segment from south Jounieh to Batroun. A greater uncertainty was found between Jiyeh and the Beirut peninsula, essentially due to members 7 and 8. The Enfeh and south Tripoli areas also presented considerable uncertainty compared to the mean value, primarily due to members 7 and 3 (31) (Fig. 3).

Based on the ensemble outputs, P_{cc} was calculated for each coastal segment as:

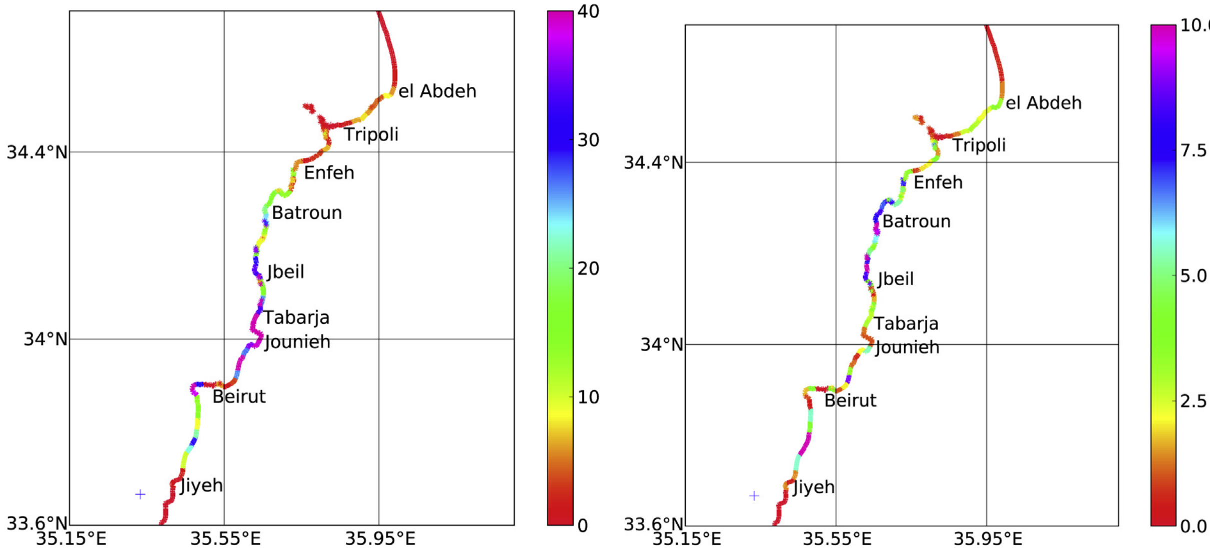
$$(P_{cc})_n = \frac{\overline{C_n}}{\overline{C}} \tag{2}$$

where $\overline{C_n}$ is the mean concentration of oil in segment n, $\overline{C}$ is the average of oil beached in all coastal segments. P_{cc} was further normalized by the maximum value of P_{cc} found in order to restrain the values along the coast between 0 and 1 (Fig. 4a). Uncertainties in P_{cc} were calculated using the coefficient of variation, CV_n (Fig. 4b), defined as:

$$CV_n = \frac{STD_n}{\overline{C_n}} \tag{3}$$

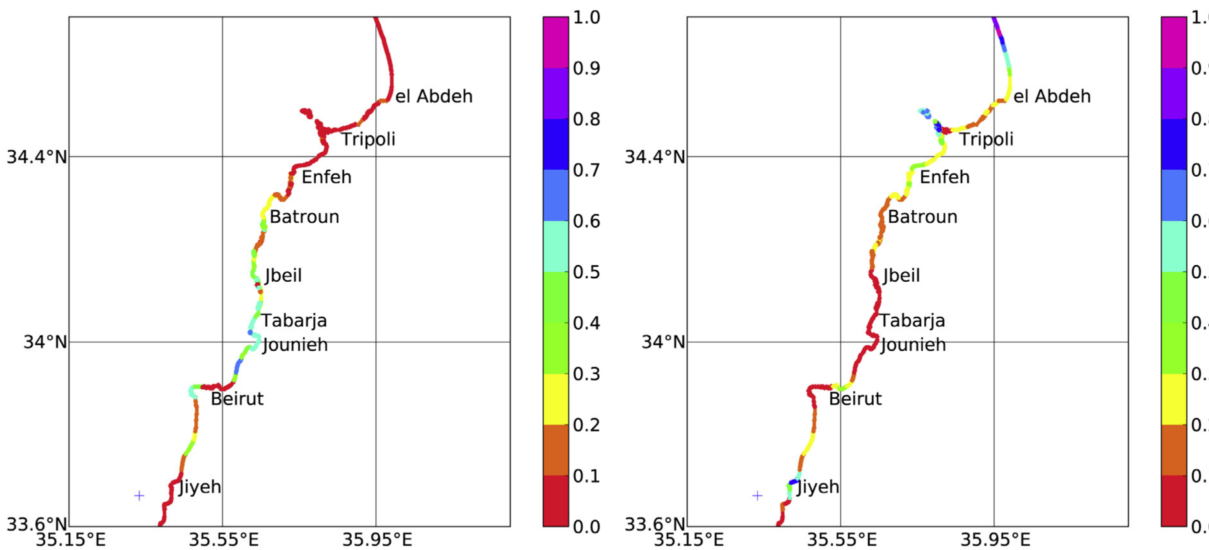
Table 4
Setup of the nine ensemble simulation members. The 9th member corresponds to the setup proposed by Coppini et al. (2011).

Configuration	Oil API	Spilled volume (tonnes)	Spill time	Spill duration (h)	Spill position
Member 1	14	18770	13/07 08:00	144	33.75N 35.33E
Member 2	26	18770	13/07 08:00	144	33.75N 35.33E
Member 3	20	10000	13/07 08:00	144	33.75N 35.33E
Member 4	20	20000	13/07 08:00	144	33.75N 35.33E
Member 5	20	18770	13/07 20:00	144	33.75N 35.33E
Member 6	20	18770	14/07 08:00	144	33.75N 35.33E
Member 7	20	18770	13/07 08:00	48	33.75N 35.33E
Member 8	20	18770	13/07 08:00	100	33.75N 35.33E
Member 9	20	18770	13/07 08:00	144	33.75N 35.33E



(a) Mean (b) Standard deviation

Fig. 3. Ensemble mean and standard deviations of beached oil for the 10/08/2006 – 06:00 – (tonnes/km).



(a) P_{cc} (b) CV

Fig. 4. Probability of oil pollution due to Jiyeh power plant accident and uncertainties in the estimation.

where STD_n is the ensemble standard deviation at n. The values shown were further normalized by the maximum CV on the coast.

Comparisons of P_{cc} with in-situ oil observations published by the Green Line Association (2007) (Fig. 5) show that areas with P_{cc} greater than 0.5 (Jounieh-Batroun region and Beirut peninsula) cover the majority of the areas in which oil was found after the spill. By including P_{cc} values between 0.3 and 0.5, we managed to incorporate areas between Jiyeh and Beirut. Discrepancies between observed and modeled beached oil occurred in Jounieh bay and in the area between the Jounieh bay and the Beirut peninsula. Pollution north of El Abdeh was detected by the Green Line Association (2007) but the model did not reproduce that. Furthermore, pollution between Jiyeh and Beirut was underestimated. The relatively coarse spatial resolution of our input dataset (i.e. hydrodynamics, coastal types and winds) are possible contributing effects to the model failure to reproduce some of the observed features.

4.4. Risk evaluation

Six outputs to support the visual communication of the oil spill risk were thus generated/compiled by our framework (Figures S1, S2 and S3 in the Supplementary Material and Figs. 3 and 4) (33). In Fig. 6 we add the calculated normalized risk in which priority protection areas in the case of future spills can be identified (34). The area just south of Jounieh presented the highest risk level ($0.2 < R < 0.7$) combining $P_{cc} > 0.6$ with a high vulnerability site and

Fig. 5. Impacted coastal sectors according to observations by Green Line Association (2007).

$CV < 0.1$. A similar scenario was found at Jbeil with R and P_{cc} above the 0.5 threshold and medium to high vulnerability. The area of Batroun also stood out, reaching higher R and P_{cc} values than 0.4 and a high confidence level ($CV > 0.1$). Three areas (i.e. the Beirut Peninsula, Jounieh bay and Tabarja) scored intermediate risk levels (>0.2) with high P_{cc} (>0.5), medium vulnerability and high confidence levels ($CV < 0.1$).

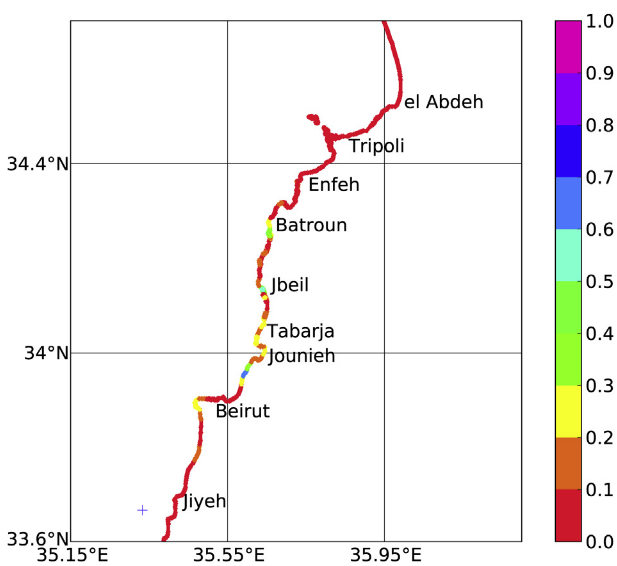


Fig. 6. Oil spill risk evaluated by equation (1) associated with Jiyeh power station for the Lebanese coast.

The final step of our framework considers risk reduction alternatives (35). According to the International Convention on Oil Pollution Preparedness, Response and Co-operation (International Maritime Organization, 1990), the reduction of oil spill risks involves various key issues: (1) a local oil pollution emergency plan, (2) an oil spill reporting system, (3) the definition of national/regional competent authorities, (4) a national contingency plan, (5) the minimum response equipment available and (6) international cooperation. As discussed in the *Establishing the Context step*, only the first (element 1 in Table 3) and third (element 4) points were fulfilled for the Lebanese case, thus making the remaining items possible alternatives for risk reduction.

5. Discussion and conclusions

The results generated by reviewing the published OSRAs showed that, to date, no standard methodology has been followed by the oil spill risk community. Compared to the latest attempt to standardize risk assessments, the ISO 31000, none of the papers fulfilled all the required items proposed by the standard. We devised and tested a new framework with 35 items by mapping the ISO 31000 to OSRAs, thus not simply translating the items of the standard, but also critically evaluating their applicability to the topic.

The case study carried out for the Lebanon crisis demonstrated that deterministic oil spill modeling can successfully predict the areas impacted by an oil spill. The application of ensemble simulations also showed that uncertainties can be addressed by combining the outputs of the ensemble members, and that relatively small changes in the oil spill characteristics may lead to significantly different results.

Seven figures were developed in the application of our framework, visually communicating the risks and replacing, in a more transparent way, the risk tolerance levels set a priori as proposed by the ISO 31000. The figures also helped to identify priority areas for protection in the case of future spills originating in Jiyeh.

Although the results obtained with the new OSRA framework for the Lebanon spill were positive and encouraging, further tests are still necessary. Only one source of risk was considered while in the future multiple sources of risk (e.g. maritime traffic, oil platforms) should be considered to give the most complete mapping of coastal oil pollution risks.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.04.044.

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