Key performance indicators for environmental contamination caused by offshore oil spills

Published Version:
Crivellari, A., Bonvicini, S., Tugnoli, A., Cozzani, V. (2021). Key performance indicators for environmental contamination caused by offshore oil spills. PROCESS SAFETY AND ENVIRONMENTAL PROTECTION, 153, 60-74 [10.1016/j.psep.2021.06.048].

Availability:
This version is available at: https://hdl.handle.net/11585/838340 since: 2021-11-13

Published:

DOI: http://doi.org/10.1016/j.psep.2021.06.048

KEY PERFORMANCE INDICATORS FOR ENVIRONMENTAL CONTAMINATION CAUSED BY OFFSHORE OIL SPILLS

Anna Crivellari, Sarah Bonvicini*, Alessandro Tugnoli, Valerio Cozzani

KEY PERFORMANCE INDICATORS FOR ENVIRONMENTAL CONTAMINATION CAUSED BY OFFSHORE OIL SPILLS

Anna Crivellari, Sarah Bonvicini*, Alessandro Tugnoli, Valerio Cozzani

LISES - DICAM, Laboratory of Industrial Safety and Environmental Sustainability of the Department of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Via Terracini 28, Bologna, 40131, Italy

*Corresponding author; e-mail address: sarah.bonvicini@unibo.it

Abstract

Oil spills during offshore operations are likely to cause severe contamination of the sea. The identification of the environmental effects of accidental releases from offshore oil and gas facilities plays a crucial role in the prevention and mitigation of marine pollution. Key Performance Indicators (KPIs) are largely recognized as an effective tool to address and communicate multifaceted issues related to accidental events in the framework of risk management. In the context of Oil Spill Risk Assessment (OSRA) studies, this study proposes a set of KPIs addressing the potential environmental contamination caused by on-surface oil spills from offshore oil and gas installations. A layered approach was defined, based on three different levels of KPIs having an increasing complexity and providing an increasing amount of information. The environmental KPIs defined allow a preliminary quantitative assessment of the environmental contamination due to the oil spill scenarios defined in the ENVironmental hazards IDentification (ENVID) studies carried out for oil and gas installations, providing a preliminary ranking of the expected environmental effects of the spills and supporting their prioritization in order to select those which should undergo a more accurate Environmental Risk Assessment study (ERA).

Keywords

Offshore oil spills; environmental contamination; KPI; oil installations; gas installations; risk assessment.

Nomenclature

°API American Petroleum Institute gravity

ADIOS Automated Data Inquiry for Oil Spills software code

AP identifier of one of the oil and gas facilities assumed in the case-studies

AP1, AP2, AP3, AP4 identifiers of the spill scenarios of facility AP

$A_{slick}(t)$ area of the slick at time t

$A_{th\ slick}(t)$ area of the thick slick at time t

ENVID ENVironmental hazards IDentification

ERA Environmental Risk Assessment

GNOME General National Oceanic and Atmospheric Administration Operational Modeling Environment software code

HNS Hazardous and Noxious Substances

KPI Key Performance Indicator

$KPI_{1.1}$, $KPI_{2.1}$, $KPI_{2.2}$, $KPI_{3.1}$, $KPI_{3.2}$ identifiers of the Key Performance Indicators defined

LNAPL Light Non Aqueous Phase Liquid

MA identifier of one of the oil and gas facilities assumed in the case-studies

MA1, MA2 identifiers of the spill scenarios of facility MA

$m_{slick}(t)$ oil mass in the slick at time t

$m_{th\ slick}(t)$ oil mass in the thick slick at time t

OSCAR Oil spill Contingency And Response software code

OSRA Oil Spill Risk Assessment

OWM Oil Weathering Model software code

RM identifier of one of the oil and gas facilities assumed in the case-studies

RM1, RM2, RM3, RM4, RM5 identifiers of the spill scenarios of facility RM

VG identifier of one of the oil and gas facilities assumed in the case-studies

VG1, VG2, VG3, VG4, VG5 identifiers of the spill scenarios of facility VG

1. Introduction

Accidental releases of hazardous materials at sea are a source of marine pollution which may result in both immediate and long-term environmental damage. Among the chemicals that may be released offshore, oil is the substance with the highest spill frequencies and volumes (ITOPF, 2012a), even if accident databases record several events involving the so-called Hazardous and Noxious Substances (HNS, i.e. chemicals soluble in water) that caused extensive harm to the water column (Law et al., 2003; Mamaca et al., 2009; Purnell, 2009; Neuparth et al., 2012; Häkkinen and Posti, 2013). The 2010 British Petroleum Deepwater Horizon blowout in the Gulf of Mexico determined the largest offshore spill in the history of the United States, with extensive pollution of all the sea compartments and significant harm to their ecosystems, in particular to the nearshore and coastal populations and to the deep-sea corals and benthic organisms (Wallace et al., 2017). Long-term effects due to the embryonic exposure to hydrocarbons may be expected for several years in fish along the water column, in addition to the immediate mortality of seabirds and benthic invertebrates on oiled shores and seafloors (Beyer et al., 2016; Clough et al., 2017; Stout et al., 2017). In 1989, the oil tanker Exxon Valdez spilled more than 42,000 m^3 of crude oil in Alaska's Prince William Sound (Guterman, 2009). The oil caused mortality of seabirds, sea otters and harbour seals, as well as of macro-algae and benthic invertebrates on the oiled shores and sea bottoms. Furthermore, long-term effects in fish along the water column became evident, because of the embryonic exposure to the oil (Peterson et al., 2003). In 1969, the barge Florida released between 650 and 700 m^3 of fuel oil into Buzzards Bay (Reddy et al., 2002). Animals were highly impacted by the oil, and massive mortality of marine life occurred in the first days after the spill, including fish, worms, crustaceans, and molluscs. Oil-covered marsh grasses died within a few weeks after the accident (White et al., 2005). It was found that petroleum-derived hydrocarbons had been persisting in the sediments and that detectable sub-lethal biological impacts in fiddler crabs, salt marsh grasses and ribbed mussels were still evident 40 years after the spill (Culbertson et al., 2007, 2008a, 2008b). Other past spills from the oil tankers Sea Empress (1996), Erika (1999), and Prestige (2002), revealed that birds approaching the sea surface, fish along the water column, shellfish and benthos living in shallow waters close to the shoreline are the living organisms mostly damaged by the oil (Neuparth et al., 2012).

The environmental damage of oil spills evidenced by the above mentioned past accidents is related to the potential contamination of all the four sea compartments, i.e. the sea surface, the water column, the sea floor, and the shoreline (French McCay, 2004; Stephansen et al., 2017). This damage depends on the severity of the contamination of each compartment caused by the oil and on the presence and the vulnerability of wildlife in the oiled area. The severity of the contamination depends on many different aspects, mainly related to the characteristics of the spill, the composition of the oil, the morpho-bathymetry of the area where the accident occurs, and the meteorological conditions during and after the spill event (API, 1999; NOAA, 2002; ITOPF, 2012b). Thus, in the context of Oil Spill Risk Assessment (OSRA), the determination of the severity of the contamination caused by offshore oil spills is of fundamental importance in order to reduce the environmental damage caused by oil spilled at sea (Li et al., 2016; Liu et al., 2016).

In the present study, first of all a review of the state-of-the-art of indexes related to the environmental consequences of oil spills was carried out, evidencing a clear gap on this issue (section 2). In order to fill this gap, a set of KPIs was defined to quantify the environmental consequences associated to on-surface accidental oil spills from offshore oil and gas operations (section 3). Then, the KPIs defined were applied to case-studies based on real oil and gas facilities, in order to test the approach and the level of information provided (section 4). The results of the case-studies were presented and extensively discussed, also providing a comparison to alternative screening approaches proposed in the literature and highlighting possible future research directions (section 5). Eventually, some conclusions were drawn (section 6).

2. State-of-the-art of indexes for the environmental consequences of oil spills

Several guidelines addressing the use of KPIs to monitor the safety performance of the chemical and process industry have been published by authoritative institutions (HSE, 2006; OECD, 2008; CCPS, 2011). Moreover, specific guidelines (API, 2010; IOGP, 2016, 2018), as well as academic publications (Vinnem et al., 2006; Vinnem, 2010; Skogdalen et al., 2011; Rui et al., 2017; Tang et al., 2018; Zhen et al., 2019) address the use of KPIs in the oil and gas industry. However, despite the awareness of the extensive environmental damage that may derive from a major accident (as a fire, an explosion, or the release of a hazardous substance to water, air or on land), most of the previous studies only provide KPIs addressing impacts on human health and asset integrity. Even a recent report issued by IOGP (IOGP, 2018), despite underlying the importance of oil spills in the context of major accidents, only considers them to define KPIs for monitoring the performance of safety barriers and not in order to express the environmental consequences of the spills. No specific document reporting the use of KPIs for the preliminary screening of the potential threat to the environment posed by on-surface oil spills seems to be present in the literature.

In fact, the scientific literature evidences the availability of numerous advanced and detailed oil spill Environmental Risk Assessment (ERA) models, as those described, for instance, in (French-McCay, 2003; Kleissen et al., 2007; Olita et al., 2012; Dongdong et al., 2015; Guo, 2017; Melaku Canu et al., 2015; Sepp Neves et al., 2015; Stephansen et al., 2017; Al Shami et al., 2017; Libre et al., 2018). Accurate ERA approaches are proposed also in some guidelines, for instance in (OLF, 2008; IPIECA-IOGP, 2013; DNV GL, 2014).

Though, risk assessment methodologies have a different scope and different features from KPI-based approaches. In fact, risk studies are aimed at providing an accurate picture of the consequences and of the risks to the environment posed by accidental oil spills, based on detailed information about the environmental conditions and the biological and economic resources in the area of the accident. Instead, in general terms the purpose of KPIs is to provide a preliminary insight into complex concepts - as process safety, environmental protection, asset integrity, and business disruption - which are difficult to capture and measure directly, as well as to communicate effectively. Consequently, KPIs should be simple to understand, based on a limited amount of input data, straightforward to calculate, and actionable, that is, they should help answering a question and provide a further action or decision to be made, based on that answer (API, 2010). The use of KPIs in supporting the decision-making during the early design stages of projects is a well-known practice for risk management in the process industry, as extensively discussed elsewhere (Landucci et al., 2008; Tugnoli et al., 2012; Crivellari et al., 2021). In this framework, focusing on offshore applications, the availability of KPIs to express the severity of marine contamination is a useful tool to provide a preliminary screening of the criticalities of alternative process and plant design options for oil and gas installations. Furthermore, during the lifecycle of an offshore installation, these KPIs could help identifying the spills whose likelihood and consequences have to be reduced by the introduction of additional safety measures, or whose risk is worth to be analysed more in detail by means of ERA studies.

In spite of the potential value of KPI-based approaches, to the knowledge of the authors, no specific method based on KPIs has been proposed to date to express the severity of the environmental contamination deriving from offshore oil spills. Thus, the present study aims at reducing this gap, introducing a layered set of KPIs aimed at a preliminary screening of the marine pollution caused by on-surface accidental oil spills from offshore oil and gas operations in fixed or floating rigs.

3. Methods and models

3.1 Framework for the definition of the Key Performance Indicators

Since the aim of the KPIs proposed in this study is to express the severity of the contamination caused by oil spills, the basic mechanisms by which an oil spill on the sea surface evolves and causes damage to the different environmental compartments are briefly recalled below.

Once released on the sea surface, the oil behaves as a Light Non Aqueous Phase Liquid (LNAPL), forming a floating slick. The slick is transported by the action of the currents and the wind. Furthermore, the oil undergoes weathering, i.e. different physical and chemical transformations, which change the volume and the form of the slick, as well as its composition and, consequently, its properties. The weathering phenomena transfer part of the oil components to the atmosphere (where they dilute rapidly) and, if waves are present, to the water column. Sedimentation on the sea bottom of the oil dispersed in the water column may occur in shallow waters, as well as stranding, if the slick drifts towards the coast. Therefore, the sea surface is the marine compartment with the highest potential to be affected by an on-surface oil spill, while the contamination of the water column occurs in a second step and only if the sea is not calm. Moreover, only in specific cases (e.g. in shallow waters or when the slick and the underlying contaminated water are shifted to the shoreline), the sea floor and the coast are impacted by the spill. Thus, the sea surface is the main compartment that needs to be considered when establishing the severity of the potential contamination of on-surface oil spills (ITOPF, 2012a, 2012b; IPIECA-

IOGP, 2015). Accordingly, in order to define simplified indicators representing the environmental contamination caused by on-surface oil spills, the set of KPIs defined in this study only refers to the sea surface contamination.

When considering the impact of an oil spill on the sea surface, the severity of the effect of the oil to the organisms living on the sea surface is represented by the surface area of the slick. In fact, oil slicks spread till infinitesimal thickness values, which correspond to enormous superficial extensions (Bonn Agreement, 2020). Though, it is widely recognized that there is a minimum thickness of the slick that causes acute effects on animals, i.e, poses immediate threats to life and health after contact with the oil, as a consequence of the oiling of the plumage of seabirds and the fur of mammals (as bears or sea otters), as well as of the damage to the lungs and other internal organs of fish (as dolphins and whales) (Scholten et al., 1996; Stephenson, 1997; O'Hara and Morandin, 2010; Helm et al., 2014). The thickness value above which acute effects are expected varies from species to species and different limit values can be retrieved in the technical literature, ranging from 1 μ to 25 μ. Rather often the threshold thickness is assumed equal to 10 μ (Koops et al., 2004; French McCay, 2009; Norsk Olje and Gass, 2018). The portion of the slick where the thickness is above the limit value is usually called the "thick slick".

Thus, it may be concluded that the more appropriate parameter to be be used for a simplified representation of the potential for environmental contamination of an oil slick is the trend over time of its surface area (Singsaas et al., 2000; French McCay, 2009). This trend depends also on the meteorological and oceanographic conditions (mainly, on the sea state and the wind; to a lower extent, on the air and sea temperatures) in the area of the accident. Nevertheless, other parameters could be adopted for an indirect simplified representation of the slick surface area following an oil spill. The simplest parameter that may be considered is the oil mass spilled into the sea (Spounge, 1999; DNV, 2011). A further parameter that may be taken into account is the oil mass in the thick slick: clearly, the larger is the amount of oil in the slick, the vaster results the slick area (Reed et al., 1995). Thus, three parameters seem suitable to be adopted to represent the severity of the environmental contamination of the sea surface, with an increasing accuracy: the spilled mass, the mass of oil in the thick slick, and the surface area of the thick slick. These parameters can be associated with three levels of KPIs providing an increasing amount of information and requiring an increasing amount of data and computational resources to be calculated.

The evolution of the contamination of subsea releases is rather different from that of on-surface leakages, since in case of a subsea leak the spilled oil first contaminates the water column, reaching the sea surface, the sea floor and the coastline with some delay (API, 1999; NOAA, 2002; ITOPF, 2012b). Thus, subsea spills require a specific approach for the calculation of their consequences. Consequently, even if subsea releases (e.g. seabed blowouts) may cause extremely relevant environmental impacts, they are out of scope of the present study, since a specific approach and specific KPIs are required for the assessment of the environmental consequences of these events. Therefore, the KPIs defined in the present study are not adequate to capture the potential consequences of subsea releases.

3.2 Definition of the Key Performance Indicators

On the basis of the above discussion about the physical parameters which are acknowledged to express the severity of the environmental consequences of oil spills, three layers and a total of five KPIs were defined to express the environmental contamination caused by offshore oil spills. The layered approach is structured so that in each layer different level of detail and calculation effort is required to assess the KPIs, and the KPIs provide a different level of information. Figure 1 shows the structure of the approach.

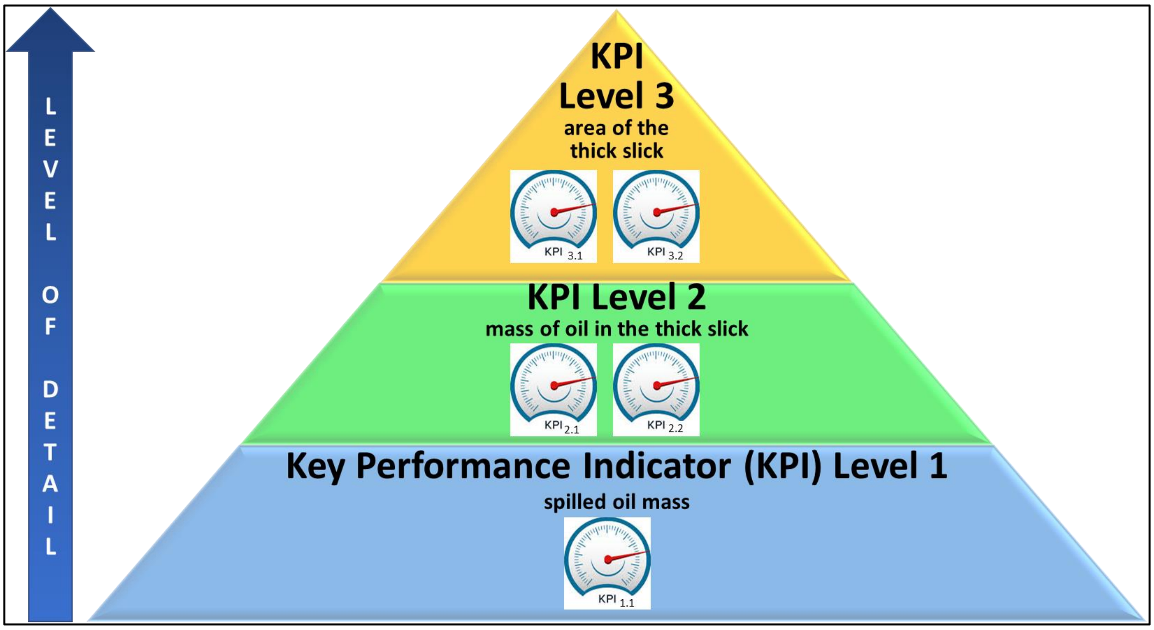

Figure 1. *Layered approach for the definition of the Key Performance Indicators*

As shown in Figure 1, a single, simple KPI constitutes the bottom layer of the approach:

$$\boldsymbol{KPI_{1.1} = m_{spill}} \tag{1}$$

where $\boldsymbol{m_{spill}}$ is the overall amount of the oil mass spilled into the sea (in tonnes), which represents the most immediate physical term for expressing the severity of the consequences of an oil spill. Clearly enough, a higher mass of oil spilled may result in more severe consequences.

At the intermediate layer (level 2) the proposed KPIs take into account the dynamic behaviour of the mass of oil in the thick slick as a first estimate of the behaviour of the surface area of the thick slick. A higher mass of oil in the slick is related to a higher potential impact of the oil spill. The intermediate layer KPIs are intended to capture this potential threat.

The mass of oil in the slick has a continuously decreasing trend over time, because of the weathering phenomena (mainly, evaporation and dispersion) (Reed at al., 1995; Aamo et al., 1997). Two KPIs were defined at level 2. The first ($KPI_{2.1}$) is based on the oil mass in the thick slick at a given reference time:

$$\boldsymbol{KPI_{2.1} = m_{th\,slick}(t_{ref})} \tag{2}$$

where $\boldsymbol{m_{th\ slick}(t)}$ (in tonnes) is the oil mass in the thick slick at a given reference time $\boldsymbol{t_{ref}}$. Thus, for the evaluation of $KPI_{2.1}$ a reference time has to be defined.

The second ($KPI_{2.2}$) considers both the amount of oil in the thick slick and its persistence in time:

$$\boldsymbol{KPI_{2.2} = \int_0^\infty m_{th\ slick}(t) \cdot dt} \tag{3}$$

Therefore, $KPI_{2,2}$ represents the oil mass exposure, expressed in tonnes·days. This KPI takes into account that the damage to wildlife is caused not only by the extension of the oil slick (that is related to the oil mass in the thick slick), but also by its persistence in time. Actually, the number of wildlife specimens coming in contact with the slick increases with both the surface extension and the duration of the slick (Reed at al., 1995).

The third level KPIs address the extension of the thick slick, which, at first, grows to a maximum, then decreases, and finally disappears (Aamo et al., 1997). Clearly enough, a wider extension of the thick slick may result in a wider potential impact, being higher the area where sensible receptors may be affected by the spill. With respect to the second level KPIs, it is evident that, at least in principle, the extension of the thick slick, although being more complex to calculate, provides a more accurate assessment of the potential environmental damage caused by the oil spill with respect to the mass of oil in the thick slick.

A first KPI is based on the maximum extension expected for the thick slick:

$$\boldsymbol{KPI_{3.1} = \max_{0 \le t \le \infty} A_{th\ slick}(t)} \tag{4}$$

where $\boldsymbol{A_{th\ lick}(t)}$ (in km^2) is the maximum extension estimated for the thick slick. A second KPI takes into account also the persistence of the thick slick:

$$\boldsymbol{KPI_{3.2} = \int_0^\infty A_{th\ slick}(t) \cdot dt} \tag{5}$$

where $KPI_{3.2}$ (in $km^2 \cdot days$) represents the oil slick surface exposure (Reed at al., 1995; Aamo et al., 1997).

3.3 Calculation of the Key Performance Indicators

For offshore oil and gas installations, the potential events leading to spills of oil and other chemicals into the sea are usually identified through a structured approach called ENvironmental hazards IDentification (ENVID), carried out during dedicated workshops with experts in Health, Safety, and Environmental issues, and in various other engineering disciplines (IPIECA-IOGP, 2013). Thus, when using the KPIs for a design-based screening of the expected criticalities of oil spills deriving from an offshore installation, the oil mass spilled into the sea needed for the calculation of the bottom layer KPI, $KPI_{1.1}$, can be retrieved directly from the documentation of the ENVironmental hazards IDentification study.

Differently, the trend with time of the oil mass in the slick and of its surface area can only be obtained from software codes able to model the oil weathering processes and, thus, to predict the fate of the oil. Several different tools are available for this purpose, as reported in (Keramea et al., 2021). Four codes, among the most well-known tools, often adopted by oil and gas operators as well as by regulatory authorities, were tested to calculate the KPIs: ADIOS2 (NOAA, 2019a), GNOME (NOAA, 2019b), OWM (SINTEF, 2019a), and OSCAR (SINTEF, 2019b). In fact, the possibility of obtaining the KPI values from the elaboration of the output of existing software tools represents an advantage for the potential users of the KPIs.

ADIOS - Automated Data Inquiry for Oil Spills and GNOME - General National Oceanic and Atmospheric Administration Operational Modeling Environment are freeware tools produced by the United States National Oceanic and Atmospheric Administration, while OWM - Oil Weathering Model and OSCAR - Oil Spill Contingency And Response are licenced codes developed by the Norwegian research institute SINTEF. They all simulate the oil weathering phenomena, although with a different level of detail. Some features of these codes are resumed in Table 1. The table only reports the characteristics which are of interest for the calculation of the above defined KPIs, a comprehensive discussion of these software tools being available in (Keramea et al., 2021).

Table 1. *Main characteristics of the software tools considered for the calculation of the Key Performance Indicators*

		Software codes			
		ADIOS2	GNOME	OWM	OSCAR
Number of oils in the database		~ 1000	7	~ 200	~ 175
Max. simulation time		5 days	3 days	5 days	50 years (~ ∞)
		Minimum set of input data			
Oil type		✓	✓	✓	✓
Spill mass		✓	✓	✓	✓
Spill duration		✓	✓	✓	✓
Spill temperature		✗	✗	✗	✓
Wind (speed and direction)		✓	✓	✓	✓
Currents (speed and direction)		✗	✓	✗	✓
Sea temperature		✓	✗	✓	✓
Air temperature		✗	✗	✗	✓
		Output data for the evaluation of the Key Performance Indicators			
$m_{slick}(t)$	oil mass in the slick	✓	✓	✓	✓
$m_{th\ slick}(t)$	oil mass in the thick slick	✗	✗	✗	✓
$A_{slick}(t)$	area of the slick	✓	✗	✗	✓
$A_{th\ slick}(t)$	area of the thick slick	✗	✗	✗	✓

Based on Table 1, it is clear that the level of detail of the input data, as well as that of the results, is very different for the four software tools considered.

It should be remarked that, with respect to the temperature values, the OSCAR software takes into account the spill temperature, the air temperature, and the sea temperature. Instead, the ADIOS and OWM codes require in input the sole sea temperature, assuming that the spill and the air are in thermal equilibrium with the sea. Lastly, the GNOME tool completely neglects the influence of the temperature on the oil spill, not considering any temperature input. With respect to the output, only the OSCAR software is able to evaluate the trend over time of the oil mass and the surface area of the whole slick and of the thick slick. Thus, in evaluating the level 2 and level 3 KPIs with the ADIOS, the GNOME, and the OWM software codes, the mass of oil and the surface area of the slick were considered as an approximate and conservative measure, respectively, of the mass of oil and of the surface area of the thick slick. Moreover, $KPI_{2.2}$, $KPI_{3.1}$, and $KPI_{3.2}$ were assessed up to the maximum simulation time admitted by each software. In an analogues way, this time was considered also as the reference time for the calculation of $KPI_{2.1}$. Consequently, since the thick slick disappears after some time, $KPI_{2.1}$ is always null if calculated with the OSCAR software which allows long simulation times and, thus, that KPI was not evaluated with this code.

4. Case-studies

Case-studies were considered to test the approach and compare the level of information provided by the different KPIs. Four real offshore facilities, located in different geographical areas and currently producing oil or gas, were taken into account (namely, the RM, VG, MA, and AP installations). Actually, the RM facility consists of a main platform, two auxiliary platforms, and a Floating Storage and Offloading (FSO) unit, connected to the main platform by a sealine. The VG installation includes a production platform and a nearby FSO unit. In the production manifold, the crude is mixed with a diluent (diesel) in order to reduce its viscosity and prevent solidification. The diluent is stored in the Floating Storage and Offloading unit and delivered to the platform through a dedicated sealine. The third platform (named MA) produces gas. On the deck of the installation there is a power generation system fuelled with marine diesel, stored in a dedicated vessel. Lastly, the AP facility produces a light crude with a water-to-oil ratio of 0.3. On the platform, the oil is first separated from water and then pumped to a header for the transportation via sealine to the nearby coast. Table 2 summarizes the main features of the platforms considered in the case-study, extracted from the design documents.

Table 2. General features of the oil and gas facilities considered in the case-studies

Oil and gas installations				
Facility ID	RM	VG	MA	AP
Country	Italy	Italy	Croatia	Rep. of Congo
Sea	Northern Adriatic Sea	Channel of Sicily	Southern Adriatic Sea	Atlantic Ocean
Product	oil	oil	gas	Oil
API°	11.5	15.4	/	28-32
Water depth (m)	80	120	69	80
Sea temperature (°C)	15	19	15	25
Air temperature (°C)	15	19	15	25

In total, 16 oil spills corresponding to continuous leakages and instantaneous releases from the equipment units present on the four facilities were considered, as reported in the ENVironmental hazards IDentification analysis performed for each installation and further considered in the Environmental Risk Assessment study and oil spill emergency response plansì of each facility. The information of each spill scenario considered in the case-studies is summarized in Table 3.

Table 3. *Data of the spill scenarios considered in the case-studies*

Facility ID	Spill ID	Substance	°API	Spill mass (t)	Order of magnitude for mass (t)	Spill duration (minutes)	Spill temperature (°C)
RM	RM1	crude	11.5	0.12	0.1	10	65
	RM2	crude	11.5	1.05	1	10	65
	RM3	crude	11.5	1.70	1	10	80
	RM4	crude	11.5	3.39	1	10	65
	RM5	crude	11.5	12,900	10,000	-	20
VG	VG1	crude	11.5	0.12	0.1	10	101
	VG2	diluent	62.3	0.44	0.1	10	20
	VG3	blend	22.9	2.74	1	10	85
	VG4	diluent	62.3	10,200	10,000	-	20
	VG5	blend	22.9	13,500	10,000	-	30
MA	MA1	diesel	35.0	0.92	1	-	20
	MA2	diesel	35.0	1.02	1	-	20
AP	AP1	crude	30.0	0.94	1	10	36
	AP2	crude	30.0	2.13	1	3	36
	AP3	crude	30.0	6.05	10	-	36
	AP4	crude	30.0	8.02	10	3	36

Table 3 shows that the 16 spills scenarios have significant differences, in particular when considering the spill mass, which varies over 5 orders of magnitude, from about 0.1 t to 10,000 t. In order to simulate the spills by the approach described in section 3.3, it was necessary to identify in the oil database of each software tool the model oil more similar to the spilled product, considering the API gravities [Lehr, 2001]. Table 4 summarizes the model oils selected for the simulations.

Table 4. *Model oils assumed for the simulation of the case-studies*

	Software codes							
	ADIOS		GNOME		OWM		OSCAR	
	Model oils selected from the oil databases of the software codes							
Spill ID	Oil name	°API	Oil name	°API	Oil name	°API	Oil name	°API
RM1 RM2 RM3 RM4 RM5	WestDeltaBlock 30	11.4	FuelOil#6	8-15	Grane	18.7	Grane	18.7
VG1	West Delta Block 3030	11.4	FuelOil#6	8-15	Grane	18.7	Grane	18.7
VG2	Naphtha Mapco	63.3	Gasoline	50-71	Sleipner	58.4	Kerosene	45.4
VG3	Carpinteria	22.9	FuelOil#4	20-24	Mandalay Battelle	20.3	Forseti2001	23.0
VG4	Naphtha Mapco	63.3	Gasoline	50-71	Sleipner	58.4	Kerosene	45.4
VG5	Carpinteria	22.9	FuelOil#4	20-24	Mandalay Battelle	20.3	Forseti 2001	23.0
MA1 MA2	Eugene Island Block 276	35	Diesel	27-41	Marine Diesel	36.4	Marine Diesel	36.4
AP1 AP2 AP3 AP4	Abu Safah Aramco	28.4	MedCrude	22-31	Norne	32.7	Eldfisk 2000	28.9

Since in the ADIOS software the minimum duration which can be assumed for a spill is equal to 1 hour, this value was adopted also for the simulation of the oil spills with the GNOME, OWM, and OSCAR software tools. Moreover, since the ADIOS code only allows considering spilled masses higher than 320 kg, the RM1, VG1, and VG2 spill scenarios were not modelled with this code.

Due to the need to limit the complexity in the calculation of the KPIs, a few simplifying assumptions were introduced concerning the huge possible combinations of wind and current fields influencing the fate of the spills. Thus, the wind and current vectors were assumed constant in time and uniform in space. The same assumption was considered for the air and sea temperatures. At the VG installation, the average values of the wind speed and of the current velocity are equal, respectively, to 6 m/s and to 0.13 m/s. Moreover, on average the wind and current vectors are orthogonal and directed so that the advection of the slick is towards the open sea. For the sake of simplicity, these wind and current data were assumed for all the facilities of the case-study, in order to get results independent from the environmental conditions, thus allowing a more simple comparison.

5. Results and Discussion

5.1. Key Performance Indicators and ranking of the spill severity in the case-studies

The values of the KPIs defined in section 3.2 calculated for all the spill scenarios considered in the case-studies described in section 4 are reported in Table 5.

Table 5. *Values of the Key Performance Indicators calculated for the oil spill scenarios considered in the case-studies*

	KPI of level 1	**KPIs of level 2**							**KPIs of level 3**			
	/	Software codes							Software codes			
	/	**ADIOS**	**GNOME**	**OWM**	**ADIOS**	**GNOME**	**OWM**	**OSCAR**	**ADIOS**	**OSCAR**	**ADIOS**	**OSCAR**
Spill ID	**$KPI_{1.1}$ (t)**	**$KPI_{2.1}$ (t)**	**$KPI_{2.1}$ (t)**	**$KPI_{2.1}$ (t)**	**$KPI_{2.2}$ (t·d)**	**$KPI_{2.2}$ (t·d)**	**$KPI_{2.2}$ (t·d)**	**$KPI_{2.2}$ (t·d)**	**$KPI_{3.1}$ (km^2)**	**$KPI_{3.1}$ (km^2)**	**$KPI_{3.2}$ ($km^2 \cdot d$)**	**$KPI_{3.2}$ ($km^2 \cdot d$)**
RM1	$1.2 \cdot 10^{-1}$	-	$8.3 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$	-	$2.8 \cdot 10^{-1}$	$5.2 \cdot 10^{-1}$	$4.1 \cdot 10^{-3}$	-	$4.4 \cdot 10^{-3}$	-	$1.9 \cdot 10^{-4}$
RM2	1.1	$9.6 \cdot 10^{-1}$	$7.4 \cdot 10^{-1}$	$9.1 \cdot 10^{-1}$	$4.2 \cdot 10^{-2}$	2.5	4.7	$6.0 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	$3.4 \cdot 10^{-2}$	$2.2 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$
RM3	1.7	1.5	1.2	1.5	$4.8 \cdot 10^{-1}$	4.1	7.5	$3.4 \cdot 10^{-1}$	$1.7 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$	$5.4 \cdot 10^{-3}$	$6.0 \cdot 10^{-3}$
RM4	3.4	2.7	2.4	2.9	$9.7 \cdot 10^{-1}$	8.1	$1.5 \cdot 10$	$8.5 \cdot 10^{-1}$	$3.4 \cdot 10^{-2}$	$4.4 \cdot 10^{-2}$	$9.6 \cdot 10^{-3}$	$1.5 \cdot 10^{-2}$
RM5	$1.3 \cdot 10^{4}$	$1.1 \cdot 10^{4}$	$9.1 \cdot 10^{3}$	$1.1 \cdot 10^{4}$	$4.2 \cdot 10^{3}$	$3.1 \cdot 10^{4}$	$5.7 \cdot 10^{4}$	$4.8 \cdot 10^{4}$	$1.3 \cdot 10^{2}$	$1.0 \cdot 10$	1.1	$3.7 \cdot 10$
VG1	$1.2 \cdot 10^{-1}$	-	$8.5 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$	-	$2.9 \cdot 10^{-1}$	$5.3 \cdot 10^{-1}$	$3.7 \cdot 10^{-4}$	-	$9.1 \cdot 10^{-5}$	-	$3.8 \cdot 10^{-6}$
VG2	$4.4 \cdot 10^{-1}$	-	$1.0 \cdot 10^{-2}$	$2.5 \cdot 10^{-2}$	-	$2.8 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$	$7.0 \cdot 10^{-3}$	-	$6.2 \cdot 10^{-3}$	-	$4.1 \cdot 10^{-4}$
VG3	2.7	1.4	1.4	2.1	$5.1 \cdot 10^{-1}$	5.6	$1.1 \cdot 10$	$6.3 \cdot 10^{-1}$	$3.0 \cdot 10^{-2}$	$2.9 \cdot 10^{-4}$	$8.5 \cdot 10^{-3}$	$7.4 \cdot 10^{-3}$
VG4	$1.0 \cdot 10^{4}$	$1.7 \cdot 10^{3}$	$6.1 \cdot 10$	$6.4 \cdot 10^{2}$	$1.2 \cdot 10^{3}$	$1.8 \cdot 10^{3}$	$5.4 \cdot 10^{3}$	$1.4 \cdot 10^{4}$	5.9	1.5	$5.4 \cdot 10^{-1}$	4.7
VG5	$1.4 \cdot 10^{4}$	$1.0 \cdot 10^{4}$	$6.8 \cdot 10^{3}$	$1.0 \cdot 10^{4}$	$1.7 \cdot 10^{4}$	$2.7 \cdot 10^{4}$	$5.2 \cdot 10^{4}$	$4.4 \cdot 10^{4}$	$1.4 \cdot 10^{2}$	$1.6 \cdot 10^{2}$	$8.2 \cdot 10$	$2.3 \cdot 10^{2}$
MA1	$9.2 \cdot 10^{-1}$	$5.6 \cdot 10^{-1}$	$3.2 \cdot 10^{-1}$	$2.1 \cdot 10^{-1}$	$3.1 \cdot 10^{-2}$	1.6	1.6	$1.6 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	$5.6 \cdot 10^{-3}$	$2.3 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$
MA2	1.0	$6.2 \cdot 10^{-1}$	$3.5 \cdot 10^{-1}$	$2.4 \cdot 10^{-1}$	$3.4 \cdot 10^{-2}$	1.8	1.8	$2.7 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	$6.0 \cdot 10^{-3}$	$2.5 \cdot 10^{-4}$	$3.7 \cdot 10^{-4}$
AP1	$9.4 \cdot 10^{-1}$	$6.3 \cdot 10^{-1}$	$5.8 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$3.3 \cdot 10^{-2}$	2.1	3.5	$6.2 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$	$3.2 \cdot 10^{-3}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$
AP2	2.1	1.2	1.3	1.5	$4.5 \cdot 10^{-1}$	4.7	7.8	$3.3 \cdot 10^{-1}$	$2.4 \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$	$7.1 \cdot 10^{-3}$	$6.5 \cdot 10^{-3}$
AP3	6.1	3.5	3.7	4.2	1.3	$1.4 \cdot 10$	$2.2 \cdot 10$	1.3	$6.8 \cdot 10^{-2}$	$7.0 \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$	$2.5 \cdot 10^{-2}$
AP4	8.0	4.7	5.0	5.5	1.7	$1.8 \cdot 10$	$3.0 \cdot 10$	1.9	$9.0 \cdot 10^{-2}$	$1.1 \cdot 10^{-1}$	$2.3 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$

Table 5 shows that, for a given spill and a given KPI, differences of one or even two orders of magnitude are present among the values calculated with the different software tools.

The KPIs summarized in Table 5 have different definitions and are expressed in different units, since they correspond to different physical terms. Consequently, while a comparison among the values of the same KPI is always possible, the values of the different KPIs cannot be immediately compared to each other. In order to verify if the different KPIs give the same ranking of the severity of the contamination caused by the oil spills within each facility, an internal normalization was carried out on each KPI and each facility by means of the min-max method (Chakraborty and Yeh, 2007). The general formula for this linear rescaling procedure allows to substitute each original KPI value *x* with its normalized value *x'*:

$$x' = \frac{x - min\{x\}}{max\{x\} - min\{x\}} \tag{6}$$

where $min\{x\}$ and $max\{x\}$ represent, respectively, the minimum and the maximum of the KPI values for the given KPI type and facility considered. By this approach, normalized values were obtained, ranging between 0 and 1, where 0 corresponds to the minimum value of the KPI in the set of interest, and 1 corresponds to the maximum value. Clearly enough, this internal normalization leads to trivial results for the MA facility, for which only two releases were considered (the contamination of the spill MA1 results, obviously, as less severe than that due to the spill MA2). The normalized KPI values for all the other facilities are shown in Figure 2. The figure also allows the comparison among the normalized KPI values calculated with different software tools.

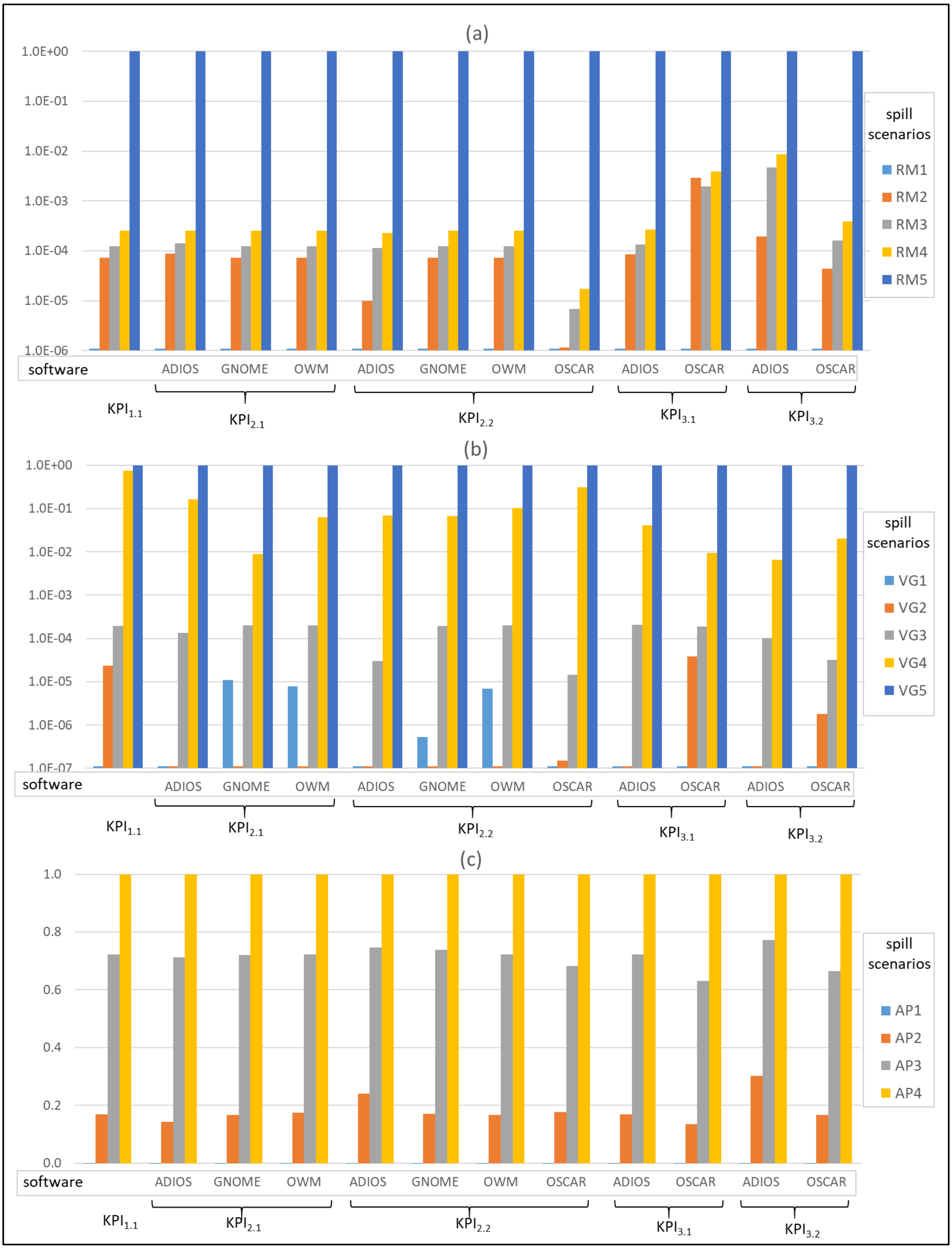

Figure 2. *Normalized Key Performance Indicators values calculated for the case-studies: (a) facility RM; (b) facility VG; (c) facility AP*

From the results displayed in Figure 2, some conclusions can be drawn about the influence on the KPIs of the spill mass, the oil type, and the spill temperature. Actually, when a different amount of the same oil having the same temperature is released, the KPIs provide the same ranking of the severity of the contamination, as evidenced by the results obtained for facility AP (Figure 2c). In fact, for facility AP, whose spills involve the same oil type and have the same temperature (as shown in Table 3), every KPI, whatever the software used for its calculation, has values that increase passing from spill AP1 (the spill with the lowest spill mass) to spill AP4 (the spill with the largest spill mass). For spills concerning the same oil type and having the same spill temperature, the larger the spill mass, the higher the value of the KPI and, thus, the severity of the environmental consequences. Therefore, for a preliminary ranking of the severity of the contamination of spills of the same oil and with the same spill temperature, it is sufficient to use the simplest KPI ($KPI_{1.1}$), which takes into account only the spill mass.

However, when a ranking among releases with different oil characteristics and / or oil temperatures is of interest, the different KPIs can give different results, as shown in Figure 2a for the RM facility. In the case of this installation, $KPI_{1.1}$ indicates that the spills RM1 to RM5 have an increasing criticality of the expected environmental consequences. The values of level 2 and 3 KPIs confirm this ranking, with the exception of $KPI_{3.1}$ when calculated with the OSCAR software, which provides an inversion of the ranking of spill RM2 and spill RM3. The cause of this inversion can be attributed to the higher temperature of spill RM3 with respect to spill RM2, despite the larger amount of the spilled mass in spill RM3, as shown in Table 3. While a higher spill mass results in a more severe environmental contamination, a higher spill temperature ensures a faster evaporation of the oil, as well as an enhanced dispersion of the oil into the sea because of its reduced viscosity: thus, a higher spill temperature results in less extended environmental consequences. Even if the spilled mass is usually the factor having the more important influence on the severity of the environmental contamination, the temperature may prevail in case of limited differences among the values of the spilled mass, as, for instance, in case of spills RM2 and RM3.

As indicated in Table 1, the ADIOS, GNOME, and OWM codes are not able to take into account the temperature difference of the spills. For this reason, the inversion in the ranking of the oil spills caused by differences in temperature is only present when the OSCAR software is used for the calculation of the KPIs.

A further factor influencing the spill ranking is the oil composition, and specifically its density. As shown in the case of facility VG (Figure 2b), $KPI_{1.1}$ indicates an increasing severity of the environmental effects when considering spills VG1 to VG5. However, $KPI_{2.1}$ and $KPI_{2.2}$, when calculated with the GNOME and OWM tools, show an inversion of the severity ranking of spills VG1 and VG2. Actually, as reported in Table 3, spill VG1 has a smaller spill mass and a higher density than spill VG2. In general, the higher the density of the spilled oil, the more serious the environmental contamination caused by the spill. In fact, light oils, with respect to heavy ones, usually have a high content of low and medium molecular mass components, which confer to the oil a high volatility, favouring its evaporation into the atmosphere. Furthermore, they are usually characterized by a low viscosity, advantaging their capability to be dispersed in the water column and increasing the effectiveness of emergency response actions (Kingston, 2002; Federici and Mintz, 2014; RSC, 2015). In the GNOME and OWM software, the influence of the oil type prevails on the role of the spill mass, and, consequently, the spill VG2 results as having more severe environmental consequences than the spill VG1. Differently, the influence of the spill mass prevails on that of the oil composition in ADIOS, therefore $KPI_{2.1}$ and $KPI_{2.2}$, when calculated with the ADIOS software, confirm the ranking obtained when considering $KPI_{1.1}$. The OSCAR software tool, taking into account the spill temperature in addition to the spill mass and its density, provides a more precise assessment of the KPIs and, thus, a more accurate ranking of the marine pollution due to the spills VG1 and VG2, suggesting that the spill VG1 has lower effects than the spill VG2.

The above discussion highlights that, when spills with different temperatures and / or different oil types are evaluated (e.g. when spills from different facilities or different reservoirs are compared), the bottom level $KPI_{1.1}$, which is based on the sole spill mass, does not represent a reliable indicator of the expected severity of the environmental consequences of the spills.

Moreover, it is evident that if oil spills with relevant temperature differences need to be compared, the higher level KPIs need to be calculated by means of the OSCAR software, because this is the only software tool that considers the role of the spill temperature. If a comparison among spills that have the same temperature, but refer to different oils, is of interest, also the ADIOS and OWM software codes are suitable for the calculation of the KPIs. Both should be preferred to the GNOME software, since their larger oil database allows a more appropriate selection of the oil to be simulated, as shown in Table 1.

In addition to the spilled mass, the actual importance of other parameters in influencing the KPI values and thus the severity of the expected environmental contamination expressed by the different KPIs was further investigated, as discussed below.

In order to systematically assess the influence of these parameters, the non-normalized KPI values calculated for spill scenarios characterized by a mass of the same order of magnitude are compared in Figures 3 to 6. As shown in Table 3, four different groups of spill scenarios may be identified on the basis of the order of magnitude of the spilled mass: i) 0.1 t spills (including spills RM1, VG1, and VG2, all showing differences in both the oil type and the spill temperature); ii) 1 t spills (including spills MA1, MA2, AP1, AP2, RM2, RM3, RM4, and VG3, again all different in both the oil type and the spill temperature); iii) 10 t spills (including spills AP3 and AP4, referring to the same oil type and with the same spill temperature); and iv) 10,000 t spills (including spills VG4, RM5, and VG5, which refer to different oil types having the same spill temperature).

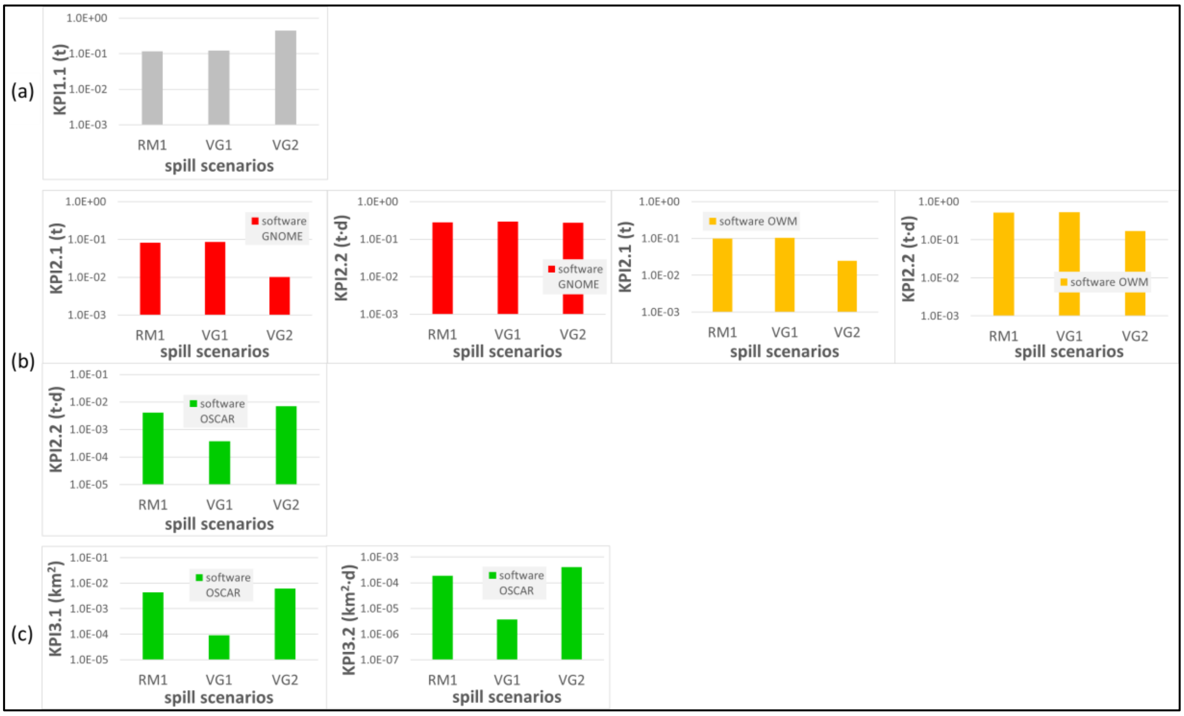

Figure 3. *Key Performance Indicators calculated using different software codes for the oil spill scenarios with spilled mass of order of magnitude 0.1 t: (a) level 1 Key Performance Indicator; (b) level 2 Key Performance Indicators; (c) level 3 Key Performance Indicators*

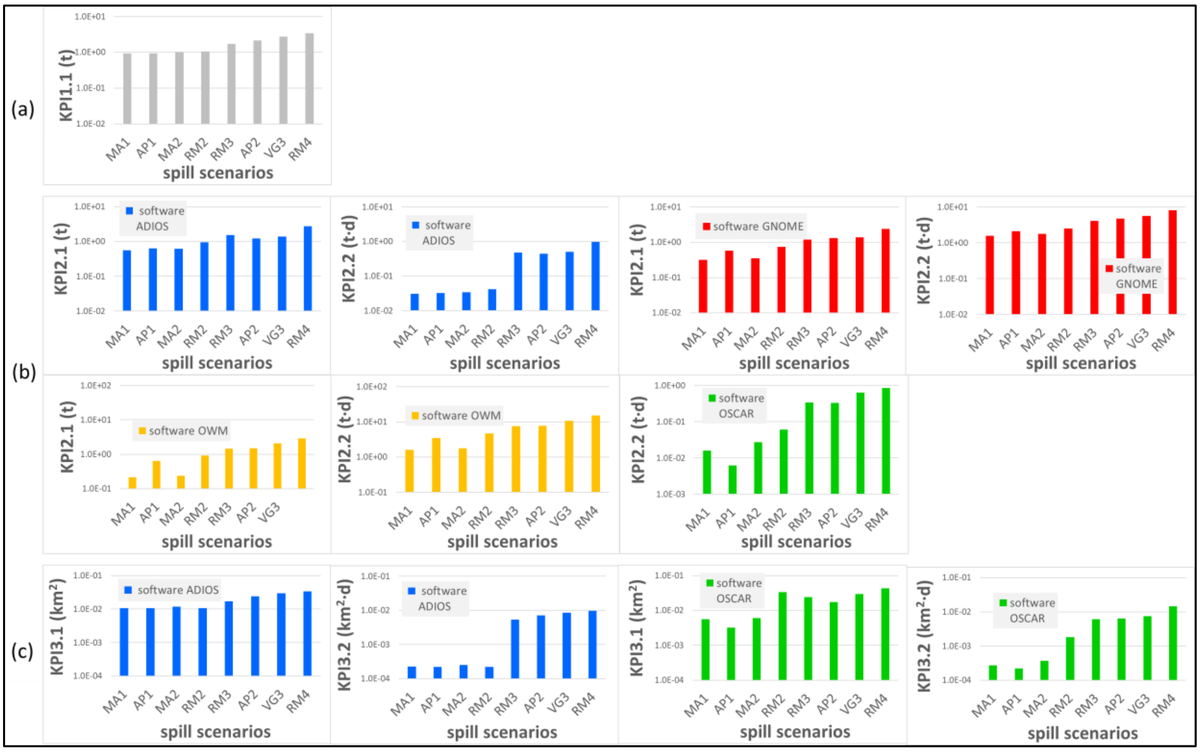

Figure 4. *Key Performance Indicators calculated using different software codes for the oil spill scenarios with spilled mass of order of magnitude 1 t: (a) level 1 Key Performance Indicator; (b) level 2 Key Performance Indicators; (c) level 3 Key Performance Indicators*

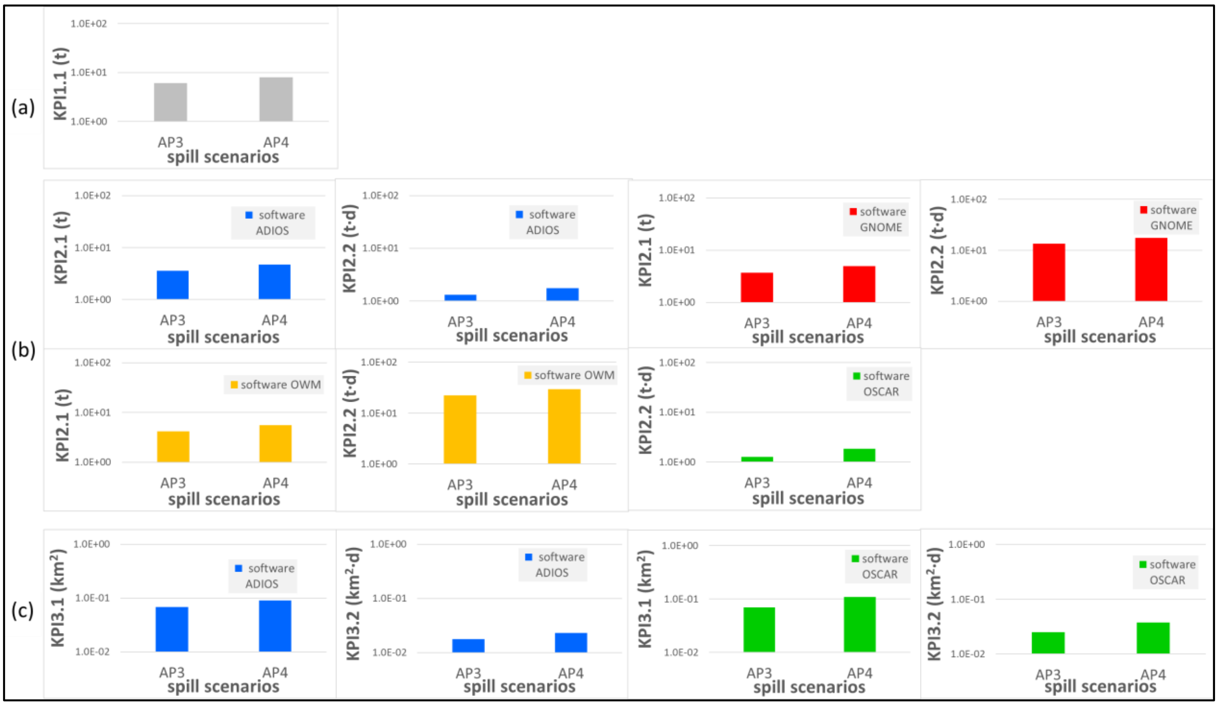

Figure 5. *Key Performance Indicators calculated using different software codes for the oil spill scenarios with spilled mass of order of magnitude 10 t: (a) level 1 Key Performance Indicator; (b) level 2 Key Performance Indicators; (c) level 3 Key Performance Indicators*

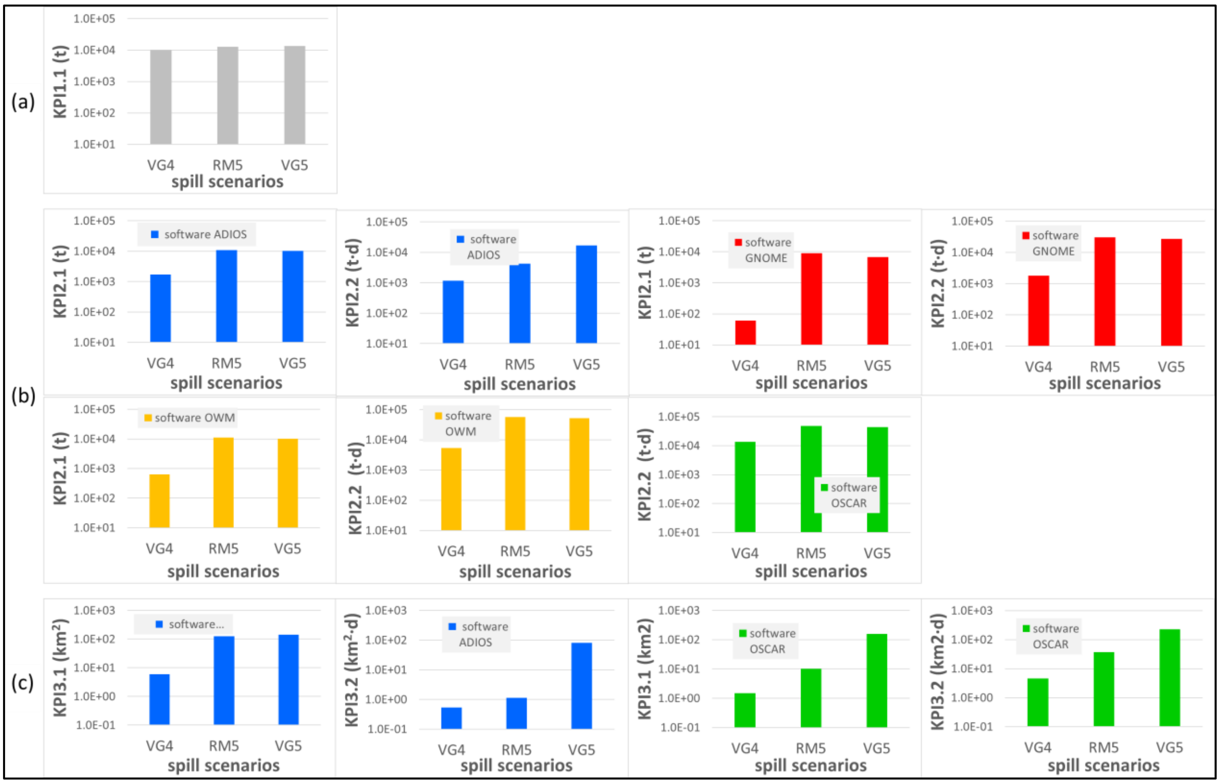

Figure 6. *Key Performance Indicators calculated using different software codes for the oil spill scenarios with spilled mass of order of magnitude 10,000 t: (a) level 1 Key Performance Indicator; (b) level 2 Key Performance Indicators; (c) level 3 Key Performance Indicators*

Quite obviously, $KPI_{1.1}$, whose values correspond to the spilled mass, has a similar value for all the spills in each group, as evident in Figures 3-6.

When Figure 5 is considered, which corresponds to spill mass values of about 10 t of the same oil type having the same spill temperature, all the KPIs indicate that the spill AP4 is slightly more severe than the spill AP3. This difference in the KPIs of the two spills has to be attributed to the slightly higher mass of spill AP4, compared to the mass of the spill AP3. Again, the results confirm once more that all the KPIs are equivalent in representing the severity of the environmental contamination caused by spills having the same composition and temperature. Thus, $KPI_{1.1}$ is adequate and sufficient to rank the environmental consequences of the spills for these scenarios.

The figures referring to the other groups of spills (Figure 3, 4 and 6) show that differences up to two orders of magnitude are present in the values of level 2 and 3 KPIs. In general, the values of level 3 KPIs present the largest differences. These can be justified keeping in mind that the fate of the spilled oil depends not only on the spill mass, but also on the oil type and the spill temperature: low density and / or high temperature spills cause a less severe contamination than high density and / or low temperature releases. Therefore, the results confirm once more that, in case of different oil types and / or spill temperatures, the sole released mass ($KPI_{1.1}$) cannot be used to rank the environmental severity of the spills.

5.2. Influence of the software tools used to calculate the Key Performance Indicators

Since, as discussed above, several different software tools are available for the calculation of the KPIs, it is important to assess specifically if and how the choice of different codes influences the KPI values obtained from the calculations. Thus, Figure 7 reports the value of each KPI calculated with the ADIOS, GNOME, OWM, and OSCAR codes.

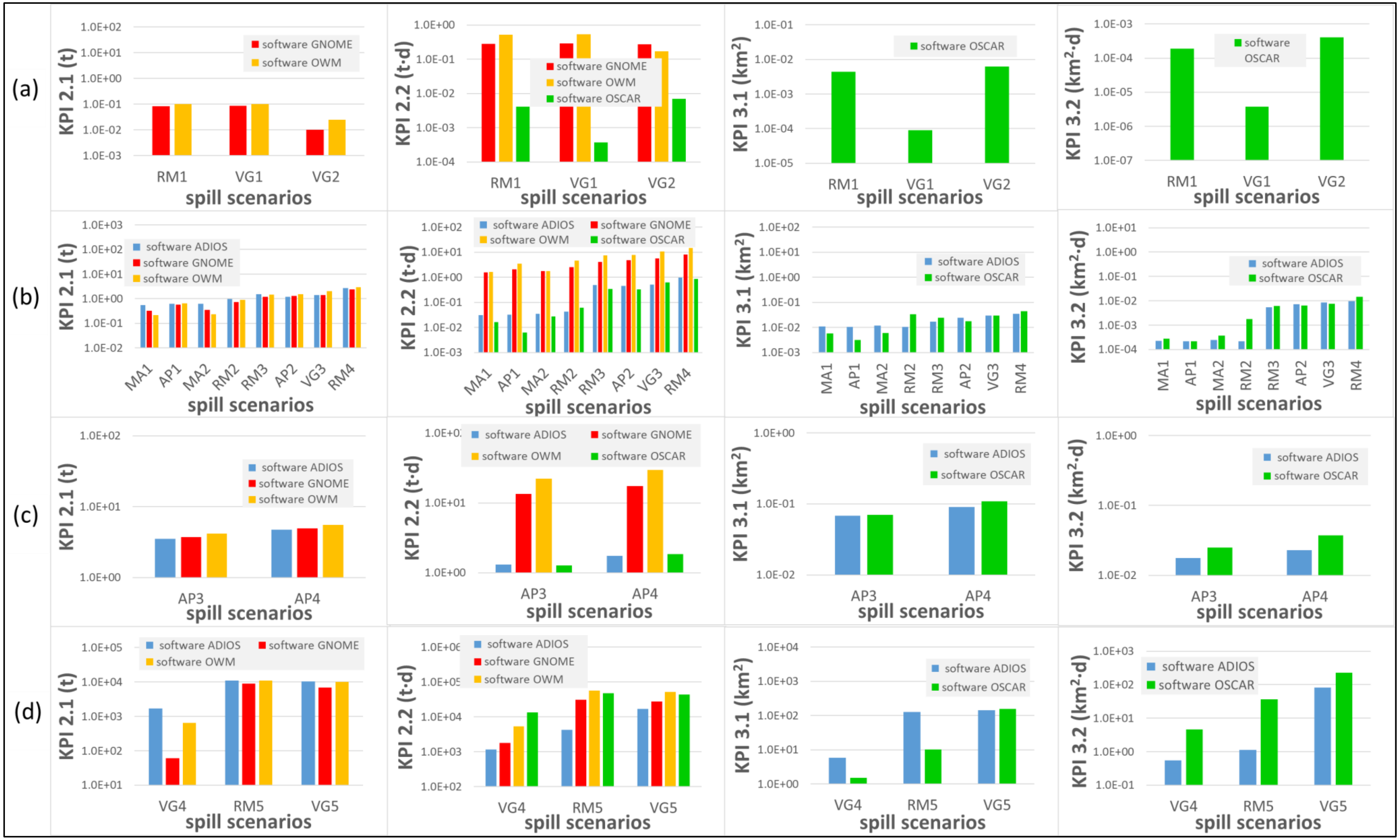

Figure 7. *Level 2 and level 3 Key Performance Indicators values for the oil spill mass categories considered: (a) 0.1 t, (b) 1 t, (c) 10 t, (d) 10,000 t*

Figure 7 clearly shows that differences of about an order of magnitude are present among the values of the KPIs calculated for the same spill with different software tools (e.g. see the values of $KPI_{2.1}$ for spill VG4, and the values of $KPI_{2.2}$, $KPI_{3.1}$, and $KPI_{3.2}$ for spills VG4 and RM5). These differences are mainly due to the different capability of the software tools to model the oil type and the spill temperature. Though, Figure 7c, which refers to two spills of about 10 t, with the same oil type and with the same spill temperature, shows that, while the values of $KPI_{2.1}$, $KPI_{3.1}$, and $KPI_{3.2}$ are similar, the values of $KPI_{2.2}$ differ of more than one order of magnitude when different software tools are used for their calculation. This difference is not related to the different input data, but has to be attributed to the different modelling approaches implemented in the software tools.

It can be concluded that the use of different software tools results in large differences in the values of the KPIs. As a consequence, a single software tool needs to be selected to obtain consistent KPIs values, even when considering spills of the same oil type and with the same spill temperature. Clearly enough, the OSCAR code should be preferred to estimate the KPI values, because its oil database gives the possibility of a more accurate selection of the oil and, in addition, this code can take into account the effects of the spill temperature on the oil fate. Moreover, if compared to the other tools, the OSCAR software is able to model a wider range of weathering phenomena and it implements more sophisticated mathematical models for their simulation, allowing a more realistic description of the behaviour of the oil slick (Reed at al., 1995; Aamo et al., 1997).

5.3. Determination of the most suitable Key Performance Indicators

From the above assessment, it clearly emerges that the bottom layer KPI can be used only for ranking the severity of the environmental consequences of oil spills having the same composition and the same temperature. This may be a relevant application when several spill scenarios are identified for a single facility (e.g. in the case of the facility AP), or for a production cluster where all the production strings process oil with a similar composition and temperature, or for facilities where the risk of environmental contamination derives from the release of substances different from the product (e.g. in gas rigs, where the diesel fuel from the emergency power supply system may be released, as in the case of facility MA).

Differently, when it is required to rank the expected severity of spill scenarios involving different facilities and / or having different composition and temperature, the higher level KPIs need to be used, in order to correctly express the potential contamination caused by the spills.

However, it is important to understand if all the second and third level KPIs are actually suitable to measure the environmental consequences of an oil spill. To address this issue, a first element to be considered concerns the software code used for the assessment of the KPIs. From the above discussion, it clearly emerges that, besides the oil mass and composition, the spill temperature is a relevant parameter in determining the environmental effects of a spill. However, only the OSCAR software allows to consider this factor in the calculation of the KPIs. Thus, a correct calculation of the higher level KPIs may only be obtained using the OSCAR software. This excludes the use of $KPI_{2,1}$, since, as discussed in section 3, this KPI cannot be calculated with the OSCAR software.

Therefore, when the severity ranking of multiple scenarios from different facilities, involving oils having different composition and different temperature, is of interest, the values of $KPI_{2.2}$, $KPI_{3.1}$, and $KPI_{3.2}$, calculated using the OSCAR software are the more significant to carry out the comparison. Figure 8 reports the upper level KPIs calculated with the OSCAR software for each of the four categories of spills defined in section 5.1.

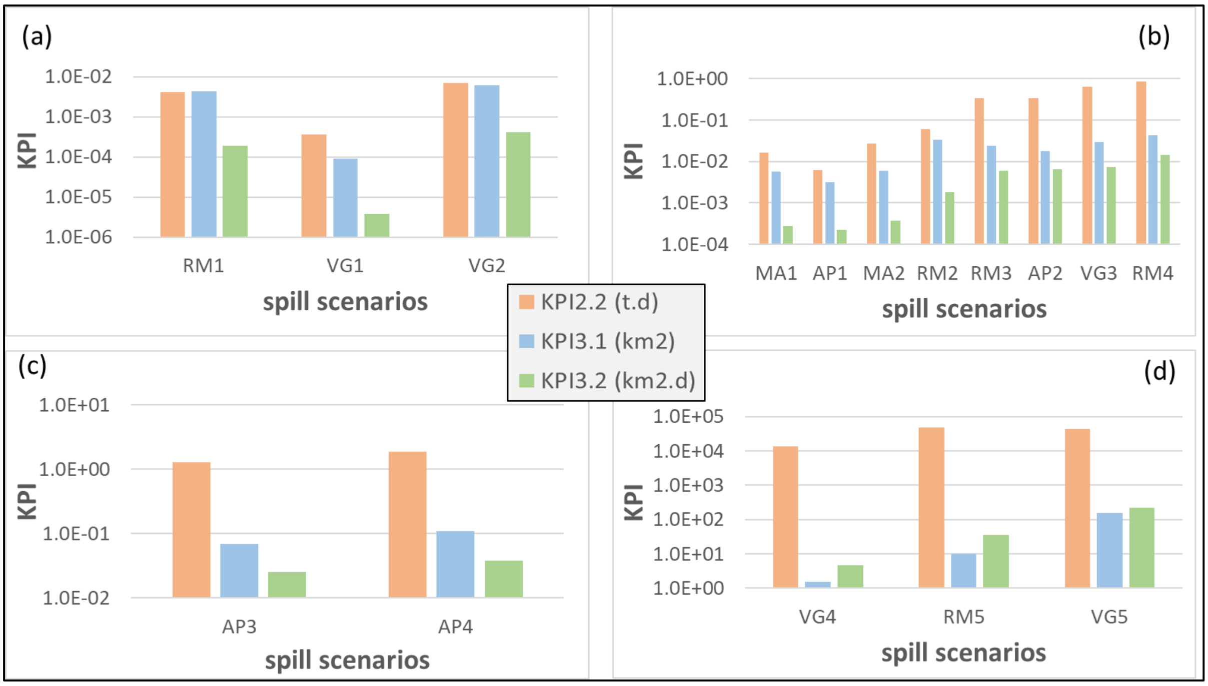

Figure 8. *Higher level Key Performance Indicators calculated using the OSCAR software for the oil spill mass categories considered: (a) 0.1 t, (b) 1 t, (c) 10 t, (d) 10,000 t*

As shown in Figure 8, $KPI_{3.1}$ and $KPI_{3.2}$ provide the same ranking of the spills for the spill categories corresponding to 0.1 t, 10 t, and 10,000 t. When considering the group of the spills having an order of magnitude of 0.1 t, both these KPIs result in the highest value for spill VG2, followed by spill RM1. The lowest values and, thus, the lowest level of criticality, corresponds to spill VG1 (Figure 8a). When considering the group of spills having an order of magnitude of 10 t, the values of $KPI_{3.1}$ and $KPI_{3.2}$, both calculated using the OSCAR software, show that spill AP3 is less hazardous than spill AP4 (Figure 8c). When considering the spills having an order of magnitude of 10,000 t, the hazard increases from spill VG4 to spill RM5, while the maximum value and thus the maximum criticality corresponds to spill VG5 (Figure 8d). In the group of spills having an order of magnitude of 1 t (Figure 8b), OSCAR $KPI_{3.1}$ and OSCAR $KPI_{3.2}$ both indicate that spills AP1, MA1, and MA2 are less hazardous than spill RM4, that results the most critical. For the other spills of this group (i.e. the spills RM2, RM3, AP2, and VG3), the two KPIs of level 3 do not give exactly the same ranking. Though, the KPI values are very similar, so that they influence the ranking but not the actual criticality of the spills.

It is also possible to notice that, in Figure 8, $KPI_{2.2}$ values, when calculated using the OSCAR software, provide a different ranking with respect to that obtained by the level 3 KPIs for spills having an order of magnitude of 10,000 t. It is thus important to understand which, among the second and third level KPIs, provides a more consistent representation of the potential for environmental contamination caused by oil spills. Since the slick surface to which the KPIs of level 3 are referred is a more precise parameter to express the environmental impact of an oil spill, the KPIs of level 3 should be preferred to second level KPIs, which are referred to the oil mass in the slick (Reed at al., 1995; Aamo et al., 1997). Thus, in Figure 8, the ranking obtained from the KPIs of level 3 should be considered more accurate than that obtained from $KPI_{2.2}$.

A further important remark is that both level 3 KPIs always provide the same ranking of the spills. In fact, the maximum area of the thick slick ($KPI_{3.1}$) shows the same behaviour of the thick slick surface exposure ($KPI_{3.2}$). Therefore, since the calculation of $KPI_{3.2}$ is more time-consuming than that of $KPI_{3.1}$, the latter may be given preference in expressing the severity of the contamination caused by oil spill scenarios, when the bottom layer KPI ($KPI_{1.1}$) is not sufficient to correctly represent their environmental effects.

5.4. Strengths and limitations of the KPI approach proposed

Due to the lack of KPIs available to express the severity of the environmental consequences of oil spills, a comparison of the proposed KPIs with other similar indicators is not possible. Moreover, the comparison of the KPIs with the results of accurate Environmental Risk Assessment (ERA) studies is not appropriate, due to the different purpose of such studies with respect to a KPI approach. However, it is important to remark that these two approaches are not to be intended as alternative, but rather complementary in the common context of Oil Spill Risk Assessment. In fact, the huge amount of data required by ERA studies, as those regarding the morpho-bathymetric features of the spill area, the environmental conditions during the year (in terms of the wind, the current, the salinity, the air, and the sea temperatures), and the description of the spatial and temporal distribution of the biological resources, makes detailed assessments costly from the point of view of the computational time. Thus, necessarily a selection of the oil spills to be further considered in the detailed assessment is needed.

Therefore, a KPI-based screening may support the ERA studies providing the identification of the most critical spills, which should receive priority in detailed Environmental Risk Assessment studies.

The limited input information necessary for the calculation of the KPIs derives from the design data of the oil and gas installation (e.g. the oil type, the spill temperature) or refer to the average environmental conditions at the site of the facility (e.g. the air and the sea temperatures, the wind and the current speed values). These data are usually known with sufficient accuracy, even in the early design steps. Differently, the estimates of the potential spill volumes stem from the techniques adopted for the ENVironmental hazard IDentification, since site-specific historical data are not available during design. Thus, spill amounts represent the best estimates provided by the experts having the task to identify the hazards.

When considering the results of the software tools for oil spill modelling, unavoidably they are affected by the uncertainty of the mathematical models implemented to describe the fate of the oil. Though, the tested software tools are developed by authoritative institutions, and are the result of extensive validation campaigns, also addressing the comparison of the results against the data referring to real oil spills. Despite the continuously ongoing research efforts for a better comprehension and a more accurate modelling of the phenomena occurring to the spilled oil (documented, for instance, in Barker et al., 2021), currently the results of oil spill software tools are considered sufficiently reliable by oil and gas operators, as well as by public authorities. Thus, the results obtained from such software tools are commonly applied to demonstrate that the risk of oil spills is acceptable and for planning oil spill emergency response actions. Therefore, their use is fully justified also inside a KPI procedure.

It should also be remarked that, as discussed above, the developed KPIs are not suitable for the assessment of subsea releases. In perspective, it seems important to introduce KPIs also to express the environmental effects of subsea oil spills, as blowouts from the seabed or leaks from sealines. In fact, in these cases the first marine compartment impacted by the oil is the water column, from which the contamination spreads to all the other compartments. Thus, specific KPIs based on parameters reflecting the damage caused by the oil to the water column are needed. Such KPIs could be also extended to Hazardous and Noxious Substances (HNS), which are completely soluble in water and, thus, inflict harm mainly to the organisms of the water column. The availability of a complete set of KPIs, applicable to all types of spills potentially caused by an oil and gas facility, would make it possible to have a thorough screening of the environmental effects of all the potential leakage scenarios.

A further remark concerns the widespread acknowledgement of the need of multi-target procedures to orient the design towards both inherently safer and more environmentally friendly solutions. Recalling that risk is usually intended as a combination of the likelihood and of the consequences of accidental events, the inclusion of the occurrence frequency of the accidental spills allows to define KPIs expressing the risk of damage to the environment of accidents occurring on oil and gas installations, integrating the information provided by the KPIs representing the environmental consequences of spills. Lastly, the combination of environmental KPIs with indicators addressing other targets, as men and assets, still remains a challenging issue on which to focus further research efforts.

6. Conclusions

In the present study, a layered set of KPIs has been introduced to express the severity of the potential environmental contamination of the sea surface caused by on-surface oil spills deriving from offshore oil and gas platforms in the open sea. The KPIs introduced allow to rank the severity of the expected environmental consequences of the spills. The bottom layer KPI defined ($KPI_{1.1}$), based on the spill mass, is adequate and sufficient to represent the severity of the contamination when spills of the same oil and the same temperature are considered. When spills of oils having different compositions and / or different temperatures are present, a software tool able to capture the influence of such differences and more accurate KPIs need to be used. In particular, the OSCAR software and the KPIs based on the area of the thick slick emerged as the most appropriate approach to estimate the effects of the spills in such cases. Although the ADIOS, GNOME, and OWM codes are useful and simple tools for the modelling of oil spills, they proved not to be suitable for the calculation of the specific KPIs developed in the present study, due to limitations mostly concerning the capability of considering the oil spill temperature.

In conclusion, the environmental KPIs defined in this study allow a preliminary quantitative representation of the potential contamination caused by on-surface oil spill scenarios identified in the ENVironmental hazards IDentification studies typically carried out for oil and gas installations, providing a ranking of the severity of the environmental consequences of the spills identified for an installation or for a set of facilities. The KPIs obtained, providing a prioritization of the oil spills, also produce a useful input to detailed Environmental Risk Assessment studies, supporting the selection of the oil spills that need to be considered more accurately. Besides, these results may be used for orienting the decision-making process in the early design phases of offshore projects. This may allow to widen the horizons of risk management in early design, by including the marine compartment amongst the targets damaged by accidents on offshore oil and gas installations. Actually, the set of KPIs provided may integrate existing KPIs, allowing to consider also damage to the environment in addition to damage to men and assets.

Acknowledgements

Support from the Italian Ministry of Economic Development, General Directorate for Safety of Mining and Energy Activities - National Office of Mining for Hydrocarbons and Geo-resources is gratefully acknowledged.

References

Aamo, O.M., Reed, M., Downing, K., 1997. Oil spill contingency and response (OSCAR) model system: sensitivity studies, in: Proceedings of the International Oil Spill Conference. 7-10 April 1997, Fort Lauderdale FL, US

Al Shami, A., Harik, G., Alameddine, I., Bruschi, D., Garcia, D.A., El-Fadel, M., 2017. Risk assessment of oil spills along the Mediterranean coast: a sensitivity analysis of the choice of hazard quantification. Sci. Total Environ. 574, 234-245. https://doi.org/10.1016/j.scitotenv.2016.09.064

API, 1999. Fate of spilled oil in marine waters: where does it go, what does it do, how do dispersants affect it? American Petroleum Institute Publication n. 4961, Washington

API, 2010. Process safety performance indicators for the refining and petrochemical industries, ANSI / American Petroleum Institute Recommended Practice n. 754, Washington

Barker, C.H., Kourafalou, V.H., Beegle-Krause, C.J., Boufadel, M., Bourassa, M.A., Buschang, S.G., Androulidakis, Y., Chassignet, E.P., Dagestad, K.F., Danmeier, D.G., Dissanayake, A.L., Galt, J.A., Jacobs, G., Marcotte, G., Özgökmen, T., Pinardi, N., Schiller, R.V., Socolofsky, S.A., Thrift-Viveros, D., Zelenke, B., Zhang, A., Zheng, Y., 2020. Progress in operational modeling in support of oil spill response. J. Mar. Sci. Eng. 8(9), 668, 1-55. https://doi.org/10.3390/jmse8090668

Beyer, J., Trannum, H.C., Bakke, T., Hodson, P.V., Collier, T.K., 2016. Environmental effects of the Deepwater Horizon oil spill: a review. Mar. Pollut. Bull. 110, 28-51. https://doi.org/10.1016/j.marpolbul.2016.06.027

Bonn Agreement, 2020. www.bonnagreement.org (accessed 10 April 2020)

CCPS, 2011, Process Safety Leading and Lagging Metrics, AIChE - CCPS American Institute of Chemical Engineers - Center for Chemical Process Safety, New York

Chakraborty, S., Yeh, C.-H., 2007. A simulation based comparative study of normalization procedures in multi-attribute decision making, in: Proceedings of the 6th WSEAS International Conference on Artificial Intelligence, Knowledge Engineering and Data Bases, pp. 102-109

Clough, J.S., Blancher, E.C., Park, R.A., Milroy, S.P., Graham, W.M., Rakocinski, C.F., Hendon, J.R., Wiggert, J.D., Leaf, R., 2017. Establishing nearshore marine injuries for the Deepwater Horizon natural resource damage assessment using AQUATOX. Ecol. Modell. 359, 258-268. https://doi.org/10.1016/j.ecolmodel.2017.05.028

Crivellari, A., Bonvicini, S., Tugnoli, A., Cozzani, V., 2021. Multi-target inherent safety indices for the early design of offshore oil and gas facilities. Process Saf. Environ. Prot. 148, 256-272. https://doi.org/10.1016/j.psep.2020.10.010

Culbertson, J.B., Valiela, I., Peacock, E.E., Reddy, C.M., Carter, A., VanderKruik, R., 2007. Long-term biological effects of petroleum residues on fiddler crabs in salt marshes. Mar. Pollut. Bull. 54, 955-962. https://doi.org/10.1016/j.marpolbul.2007.02.015

Culbertson, J.B., Valiela, I., Olsen, Y.S., Reddy, C.M., 2008a. Effect of field exposure to 38-year-old residual petroleum hydrocarbons on growth, condition index, and filtration rate of the ribbed mussel Geukensia demissa. Environ. Pollut. 154, 312-319. https://doi.org/10.1016/j.envpol.2007.10.008

Culbertson, J.B., Valiela, I., Pickart, M., Peacock, E.E., Reddy, C.M., 2008b. Long-term consequences of residual petroleum on salt marsh grass. J. Appl. Ecol. 45, 1284-1292. https://doi.org/10.1111/j.1365-2664.2008.01477.x

DNV, 2011. Assessment of the Risk of Pollution from Marine Oil Spills in Australian Ports and Waters, report n. PP002916 prepared for the Australian Maritime Safety Authority, London, UK

DNV GL, 2014. Development of methodology for calculations of environmental risk for the marginal ice zone, Report n. 2014-0545

Dongdong, L., Bin, L., Chenguang, B., Minghui, M., Yan, X., Chunyan, Y., 2015. Marine oil spill risk mapping for accidental pollution and its application in a coastal city. Mar. Pollut. Bullet. 96, 220-225. https://doi.org/10.1016/j.marpolbul.2015.05.023

Federici, C. and Mintz, J., 2014. Oil Properties and Their Impact on Spill Response Options, Report of CNA Analysis & Solutions for the US Department of the Interior, Bureau of Safety and Environmental Enforcement

French McCay, D., 2003. Development and application of damage assessment modeling: example assessment for the North Cape oil spill. Mar. Pollut. Bullet. 47, 341-359. https://doi.org/10.1016/S0025-326X(03)00208-X

French McCay, D., 2004. Oil spill impact modelling: development and validation. Environ. Toxicol. Chem. 23(10), 2441-2456

French McCay, D., 2009. State-of-the-Art and Research Needs for Oil Spill Impact Assessment Modeling, in: Proceedings of the 32nd AMOP Technical Seminar on Environmental Contamination and Response, pp. 601-653

Guo, W., 2017. Development of a statistical oil spill model for risk assessment. Environ. Pollut. 230, 945-953. https://doi.org/10.1016/j.envpol.2017.07.051

Guterman, L., 2009. Exxon Valdez turns 20. Science. 323 (5921), 1558-1559. https://doi.org/10.1126/science.323.5921.1558

Häkkinen, J.M., Posti, A.I., 2013. Overview of maritime accidents involving chemicals worldwide and in the Baltic sea. Mar. Navig. Saf. Sea Transp. Marit. Transp. Shipp. 8(2), 15-25. https://doi.org/10.12716/1001.08.02.16

Helm, R.C., Costa, D.P., DeBruyn, T.D., O'Shea, T.J., Wells, R.S., Williams, T.M., 2014. Overview of effects of oil spills on marine mammals, in Handbook of Oil Spill Science and Technology, Fingas, M.F. ed., Wiley, Hoboken NJ, US

HSE, 2006. Developing process safety indicators, Health and Safety Executive, UK

IOGP, 2016. Process safety - Leading Key Performance Indicators, International Association of Oil and Gas Producers, Report n. 556, London, UK

IOGP, 2018. Process safety - Recommended practice on Key Performance Indicators, International Association of Oil and Gas Producers, Report n. 456, London, UK

IPIECA-IOGP, 2013. Oil spill risk assessment and response planning for offshore installations, International Association of Oil and Gas Producers - Global Oil and Gas Industry Association for Environmental and Social Issues, London, UK

IPIECA-IOGP, 2015. Impacts of oil spills on marine ecology, International Association of Oil and Gas Producers - Global Oil and Gas Industry Association for Environmental and Social Issues, London

ITOPF, 2012a. Response to Marine Chemical Incidents, ITOPF - The International Tanker Owners Pollution Federation Limited, Technical Information Paper n. 17, London, UK

ITOPF, 2012b. Fate of Oil Marine Oil Spills, ITOPF - The International Tanker Owners Pollution Federation Limited, Technical Information Paper n. 2, London, UK

Keramea, P., Spanoudaki, K., Zodiatis, G., Gikas, G., Sylaios, G., 2021. Oil spill modeling: a critical review on current trends, perspectives, and challenges. J. Mar. Sci. Eng. 9 (181), 1-38. https://doi.org/10.3390/jmse9020181

Kingston, P.F., 2002. Long-term Environmental Impact of Oil Spills. Spill Sci. Technol. B. 7(1-2), 53–61

Kleissen, F., Arentz, L., Reed, M., Johansen, O., 2007. Marine environmental risk assessment system: conceptual design and preliminary demonstration for the Dutch Continental Shelf, SINTEF and WL Delft Hydraulics report n. Z4339, Delft, NL

Koops, W., Jak, R.G., van der Veen, D.P.C., 2004. Use of dispersants in oil spill response to minimize environmental damage to birds and aquatic organisms, in: InterSpill 2004 Conference Proceedings, paper n. 429

Landucci, G., Tugnoli, A., Cozzani, V., 2008. Inherent safety key performance indicators for hydrogen storage systems. J. Hazard. Mater. 159(2), 554-566. https://doi.org/10.1016/j.jhazmat.2008.02.080

Law, R.J., Kelly, C., Matthiessen, P., Aldridge, J., 2003. The loss of the chemical tanker Ievoli Sun in the English Channel, October 2000. Mar. Pollut. Bull. 46, 254-257. https://doi.org/10.1016/S0025-326X(02)00222-9

Lehr, W.J., 2001. Review of modeling procedures for oil spill weathering behavior. Adv. Ecol. Sci. 9, 51-90

Li, X., Chen, G., Zhu, H., 2016. Quantitative risk analysis on leakage failure of submarine oil and gas pipelines using Bayesian network. Process Saf. Environ. Prot. 103, 163-173. https://doi.org/10.1016/j.psep.2016.06.006

Libre, J.M., Collin-Hansen, C., Kjeilen-Eilertsen, G., Waterloo Rogstad, T., Stephansen, C., Brude, O.W., Bjorgesaeter, A., Brönner, U., 2018. ERA Acute-Implementation of a New Method for Environmental Risk Assessment of Acute Offshore Oil Spills, SPE - Society of Petroleum Engineers International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility, 16-18 April 2018, Abu Dhabi, UAE, SPE-190540-MS

Liu, R., Hasan, A.R., Ahluwalia, A., Mannan, M.S., 2016. Well specific oil discharge risk assessment by a dynamic blowout simulation tool. Process Saf. Environ. Prot. 103, 183-191. https://doi.org/10.1016/j.psep.2016.06.037

Mamaca, E., Girin, M., Le Floch, S., El Zir, R., 2009. Review of chemical spills at sea and lessons learnt. Technical appendix to the White Paper for the Interspill Conf. 4th IMO RandD Forum 40

Melaku Canu, D., Solidoro, C., Bandelj, V., Quattrocchi, G., Sorgente, R., Olita, A., Cucco, A., 2015. Assessment of oil slick hazard and risk at vulnerable coastal sites. Mar. Pollut. Bullet. 94(1-2), 84-95. https://doi.org/10.1016/j.marpolbul.2015.03.006

Neuparth, T., Moreira, S.M., Santos, M.M., Reis-Henriques, M.A., 2012. Review of oil and HNS accidental spills in Europe: identifying major environmental monitoring gaps and drawing priorities. Mar. Pollut. Bull. 64, 1085-1095. https://doi.org/10.1016/j.marpolbul.2012.03.016

NOAA, 2002. Trajectory Analysis Handbook, National Oceanic and Atmospheric Administration - Ocean Service Office of Response and Restoration - Hazardous Materials Response Division, Washington

NOAA, 2019a. Automated Data Inquiry for Oil Spills (ADIOS) Software https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/adios.html (accessed 9 April 2019)

NOAA, 2019b. General NOAA Operational Modeling Environment (GNOME) Software https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome.html (accessed 9 April 2019)

Norsk Olje and Gass, 2018. ERA Acute Report 3– Surface compartment

OECD, 2008. Guidance on safety performance indicators related to chemical accident prevention, preparedness and response for industry, Organization for Economic Coordination and Development Environment, Health and Safety Publications, Series on Chemical Accidents n. 19, Paris, F

O'Hara, P.D. and Morandin, L.A., 2010. Effects of sheens associated with offshore oil and gas development on the feather microstructure of pelagic seabirds. Mar. Pollut. Bull. 60(5), 672–678. https://doi.org/10.1016/j.marpolbul.2009.12.008

OLF, 2008. Metodikk for miljørisiko på fisk ved akutte Oljeutslipp, DNV Rapport n. 2007-2075 for Oljeindustriens Landsforening (in Norwegian)

Olita, A., Cucco, A., Simeone, S., Ribotti, A., Fazioli, L., Sorgente, B., Sorgente, R., 2012. Oil spill hazard and risk assessment for the shorelines of a Mediterranean coastal archipelago. Ocean Coast. Manage. 57, 44-52. https://doi.org/10.1016/j.ocecoaman.2011.11.006

Peterson, C.H., Rice, S.D., Short, J.W., Esler, D., Bodkin, J.L., Ballachey, B.E., Irons, D.B., 2003. Long-term ecosystem response to the Exxon Valdez oil spill. Science. 302(5653), 2082-2086. https://doi.org/0.1126/science.1084282

Purnell, K., 2009. Are HNS spills more dangerous than oil spills? A White Paper for the Interspill 2009 Conference and the 4th IMO RandD Forum

Reddy, C.M., Eglinton, T.I., Hounshell, A., White, H.K., Xu, L., Gaines, R.B., Frysinger, G.S., 2002. The West Falmouth oil spill after thirty years: the persistence of petroleum hydrocarbons in marsh sediments. Environ. Sci. Technol. 36, 4754-4760. https://doi.org/10.1021/es020656n

Reed, M., Aamo, O.M., Daling, P.S., 1995. Quantitative analysis of alternate oil spill response strategies using OSCAR. Spill Sci. Technol. B. 2(1), 67-74. https://doi.org/10.1016/1353-2561(95)00020-5

RSC, 2015. Behaviour and Environmental Impacts of Crude Oil Released into Aqueous Environments, The Royal Society of Canada, Ottawa ON, CA

Rui, Z., Li, C., Peng, F., Ling, K., Chang, H., 2017. Development of industry performance metrics for offshore oil and gas project. J. Nat. Gas Sci. Eng. 39, 44-53. https://doi.org/10.1016/j.jngse.2017.01.022

Scholten M.C.Th., Kaag, N.H.B.M., Dokkum, H.P., van, Jak R.G., Schobben, H.P.M., Slob W., 1996. Toxische effecten van olie in het aquatische milieu, TNO report TNO-MEP R96/230, Den Helder, NL

Sepp Neves, A.A., Pinardi, N., Martins, F., Janeiro, J., Samaras, A., Zodiatis, G., De Dominicis, M., 2015. Towards a common oil spill risk assessment framework - Adapting ISO 31000 and addressing uncertainties. J. Environ. Manage. 159, 158-168. https://doi.org/10.1016/j.jenvman.2015.04.044

Singsaas, I., Reed, M., Daling, P.S., 2000. Use of a Recently Developed Model System in Oil Spill Response Analysis, paper presented at the SPE International Conference on Health, Safety, and the Environment in Oil and Gas Exploration and Production 26-28 June 2000, Stavanger, N

SINTEF, 2019a. Oil Spill Contingency and Response (OSCAR) [WWW Document]. URL https://www.sintef.no/en/software/oscar/ (accessed 9 April 2019)

SINTEF, 2019b. Oil Weathering Model (OWM) User's Manual, version 10.0.0

Skogdalen, J.E., Utne, I.B., Vinnem, J.E., 2011. Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts. Saf. Sci. 49(8-9), 1187-1199. https://doi.org/10.1016/j.ssci.2011.03.012

Spounge, J., 1999. A guide to quantitative risk assessment for offshore installations, CMPT - Center for Marine and Petroleum Technology publication 99/100, UK

Stephansen, C., Bjørgesæter, A., Brude, O.W., Brönner, U., Kjeilen-Eilertsen, G., Libre, J.M., Waterloo Rogstad, T., Fjeld Nygaard, C., Sørnes, T., Skeie, G.M., Jonsson, H., Rusten, M., Nordtug, T., Reed, M., Collin-Hansen, C., Damsgaard, J., 2017. ERA Acute - a multi-compartment quantitative risk assessment methodology for oil spills, poster presented at the International Oil Spill Conference 15-18 May 2017, Long Beach CA, US

Stephenson, R., 1997. Effects of oil and other surface-active organic pollutants on aquatic birds. Environ. Conserv. 24(2), 121-129

Stout, S.A., Rouhani, S., Liu, B., Oehrig, J., Ricker, R.W., Baker, G., Lewis, C., 2017. Assessing the footprint and volume of oil deposited in deep-sea sediments following the Deepwater Horizon oil spill. Mar. Pollut. Bull. 114, 327-342. https://doi.org/10.1016/j.marpolbul.2016.09.046

Tang, K.H.D., Md Dawal, S.Z., Olugu, E.U., 2018. A review of the offshore oil and gas safety indices. Saf. Sci. 109, 344-352. https://doi.org/10.1016/j.ssci.2018.06.018

Tugnoli, A., Landucci, G., Salzano, E., Cozzani, V., 2012. Supporting the selection of process and plant design options by inherent safety KPIs. J. Loss Prevent. Proc. 25(5) 830-842. https://doi.org/10.1016/j.jlp.2012.03.008

Vinnem, J.E., Aven, T., Husebø, T., Seljelid, J., Tveit, O.J., 2006. Major hazard risk indicators for monitoring of trends in the Norwegian offshore petroleum sector. Reliab. Eng. Syst. Saf. 91 (7), 778-791. https://doi.org/10.1016/j.ress.2005.07.004

Vinnem, J.E., 2010. Risk indicators for major hazards on offshore installations. Saf. Sci. 48 (6), 770-787. https://doi.org/10.1016/j.ssci.2010.02.015

Wallace, B.P., Brosnan, T., McLamb, D., Rowles, T., Ruder, E., Schroeder, B., Schwacke, L., Stacy, B., Sullivan, L., Takeshita, R., Wehner, D., 2017. Effects of the Deepwater Horizon oil spill on protected marine species. Endang. Species Res. 33, 1-7. https://doi.org/10.3354/esr00789

White, H.K., Xu, L., Lima, A.L.C., Eglinton, T.I., Reddy, C.M., 2005. Abundance, composition, and vertical transport of PAHs in marsh sediments. Environ. Sci. Technol. 39, 8273-8280. https://doi.org/10.1021/es050475w

Zhen, X., Vinnem, J.E., Næss, S., 2019. Building safety in the offshore petroleum industry: development of risk-based major hazard risk indicators at a national level. Process Saf. Environ. Prot. 128, 295-306. https://doi.org/10.1016/j.psep.2019.06.006