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Marine oil spill risk mapping for accidental pollution and its application in a coastal city

Lan Dongdong, Liang Bin *, Bao Chenguang, Ma Minghui, Xu Yan, Yu Chunyan

National Marine Environmental Monitoring Center, Dalian 116023, China

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ABSTRACT

Accidental marine oil spill pollution can result in severe environmental, ecological, economic and other consequences. This paper discussed the model of Marine Oil Spill Risk Mapping (MOSRM), which was constructed as follows: (1) proposing a marine oil spill risk system based on the typical marine oil spill pollution accidents and prevailing risk theories; (2) identifying suitable indexes that are supported by quantitative sub-indexes; (3) constructing the risk measuring models according to the actual interactions between the factors in the risk system; and (4) assessing marine oil spill risk on coastal city scale with GIS to map the overall risk. The case study of accidental marine oil spill pollution in the coastal area of Dalian, China was used to demonstrate the effectiveness of the model. The coastal areas of Dalian were divided into three zones with risk degrees of high, medium, and low. And detailed countermeasures were proposed for specific risk zones.

1. Introduction

Accidents leading to marine environmental pollution are often an indirect consequence of rapid industrial development. In China, 3000 oil spill pollution accidents occurred in the period 1973–2011 according to the reports (Ministry of Transport, 1974–2012). Of these, several caused major environmental, social, and economic damage. Examples include oil spill incidents of the "19–3" oil spill in 2011 (Penglai), the "7–16" oil spill in 2010 (Dalian), the Gulf of Mexico oil spill in 2010 (Mexico), the Pearl River estuary oil spill in 2004 (Pearl River estuary), and Tasman oil spill in 2002 (Tianjin). These major oil spill incidents have become an important factor in destructing the marine environment and human health. Although the frequency of these incidents is low, the damage is huge because of the paroxysmal and devastating, which can cause serious ecological and environmental damage to the surrounding sea areas, Furthermore, it can cause imbalance of regional marine ecological system. There is a growing awareness and attention to the marine environmental problems caused by marine oil spill pollution accidents. A scientific and rational risk mapping of marine oil spill pollution accidents in an area can provide important information for preventing and mitigating such pollution accidents.

At present, studies on marine oil spill pollution accidents are mostly concentrated on the probability analysis (Abascal et al., 2010), prediction model (Seegey, 2000; Bollt et al., 2012) and ecological damage assessment (Mishra et al., 2012; Yang, 2014). Hazard assessment for regional sea waters (Milena et al., 2010; Davide et al., 2013; Romero et al., 2013; Ciappa and Costabile, 2014), vulnerability assessment for coastal areas (Castanedo et al., 2009; Olita et al., 2012; Alves et al., 2014) and coastal zone management (Liu, 2010) for marine oil spill pollution accidents have also been discussed, but the theories and assessment approaches of marine oil spill risk are still in a development stage. Most of these approaches are ineffective and not widely used because of the incomplete index system and over-simplified model.

Risk mapping is relatively mature in the areas of environmental risk and natural disaster, especially in natural disaster area, which can provide a basis for marine oil spill risk mapping. There are two basic approaches on natural disaster mapping named "the up-down route" and "the bottom-up route" (Wang and Shi, 1999). The environmental risk mapping approach is still in its infancy, and the approaches used include overlapping surfaces (Kuchuk et al., 1998; Gupta et al., 2002), expert judgment (Merad et al., 2004), and comprehensive regionalization (Yang et al., 2006). The oil spill risk mapping approaches on sensitivity and port district have been preliminarily developed by Arthur (Arthur et al., 2007), however, the approaches cannot accurately reflect the size and the formation mechanism of marine oil spill risk because

* Corresponding author.
E-mail address: bliang@nmemc.org.cn (B. Liang).

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of strong uncertainty, inappropriate index system, and over-simplified model. In general, the marine oil spill risk mapping approach is still immature and needs further study.

This paper describes a marine oil spill mapping approach that includes a fully completed risk indexing system and an appropriate quantitative model. The approach applied the hierarchical system including typical pollution statistics, experience from experts and the Geographical Information Systems. The coastal area of Dalian was used to demonstrate the accuracy and practical implementation of the approach.

2. Methodology and materials

2.1. Marine oil spill risk system

Starting with the typical cases of marine oil spill pollution accidents that occurred all over the world, the parameter causative factors, and formation mechanism are analyzed by scenario analysis and SPSS statistical analysis. The theories of natural disaster system and environmental risk system are referenced in the concept and composition of the marine oil spill risk system (Shi, 1996; Liu and Lei, 2003; Yang et al., 2006; Yin et al., 2007; Lan et al., 2009). Fig. 1. Here, a marine oil spill pollution accident is deemed to have occurred when a marine oil spill pollution hazard is triggered and its impacts on a vulnerable risk receptor are sufficient to cause damage. The marine oil spill risk system includes risk source and risk receptor. The risk source is anything that may cause oil spill pollution, which depends on the state of risk factors, predisposing factors, and the controls. The risk receptor is anything that is vulnerable to the oil spill damage, which depends on the degree of exposure and the resilience.

2.2. Index system

The marine oil spill risk indexes should have the characteristics that discriminate the degree of oil spill risk for each unit, Furthermore, the indexes should be complete, operative, causative, scientific and independent (Liu et al., 2010, 2013). In this paper, the index system is constructed based on the study of marine oil spill risk system (Table 1). The objective layer is the marine oil spill risk, which is determined by hazard of risk source and vulnerability of risk receptor in the medium 1 layer. Hazard is determined by risk factors state, predisposing factor, and control state in the medium 2 layer. Vulnerability is determined by exposure and resilience of risk receptor in the medium 2 layer.

There are 17 indexes in the parameter layer used to express the above indexes. Of these, four indexes are selected to describe the risk factors state, involving condition of wharfs (H_{11}), level of technical equipment (H_{12}), dispersion of channel (H_{13}) and distance of oil reserve bases (H_{14}). Annual average wind speed (H_{21}), annual foggy days (H_{22}), average wave height (H_{23}), duration of ice age (H_{24}) and water depth (H_{25}) are used to describe predisposing factors. The effectiveness of control state is represented by emergency input of sea area (H_{31}) and emergency plan of sea area (H_{32}). Marine eco-environmental sensitivity (V_{11}), coast type (V_{12}), biodiversity (V_{13}), biomass (V_{14}) are selected to represent the degree of exposure. Tidal velocity (V_{21}) and annual rainfall (V_{22}) are selected to express the capacity of resiliency to the oil spill pollution accidents.

Table 1
Mapping index system for marine oil spill risk.

Objective	Medium 1	Medium 2	Parameter
Marine oil spill risk (R)	Hazard (H)	Risk factors state (H_1)	Condition of wharfs H_{11}
			Level of technical equipment H_{12}
			Dispersion of channel H_{13}
			Distance of oil reserve bases H_{14}
		Predisposing factors (H_2)	Annual average wind speed H_{21}
			Annual foggy days (visibility less than 1 km) H_{22}
			Average wave height H_{23}
			Duration of ice age H_{24}
			Water depth H_{25}
		Control state (H_3)	Emergency input of sea area H_{31}
			Emergency plan of sea area H_{32}
	Vulnerability (V)	Exposure (V_1)	Marine eco-environmental sensitivity V_{11}
			Coast type V_{12}
			Biodiversity V_{13}
			Biomass V_{14}
		Resilience (V_2)	Tidal velocity V_{21}
			Annual rainfall V_{22}

2.3. Risk measuring models

Marine oil spill risk system is very complex and has a lot of uncertainties, which is difficult to express the relationship of components quantificationally. The empirical formulae for evaluating the risk indexes in the index system are listed in Table 2. The empirical formulae are constructed based on the actual interactions between the factors and their causative sub-factors (Table 2). The formulae are mostly obtained from the typical cases

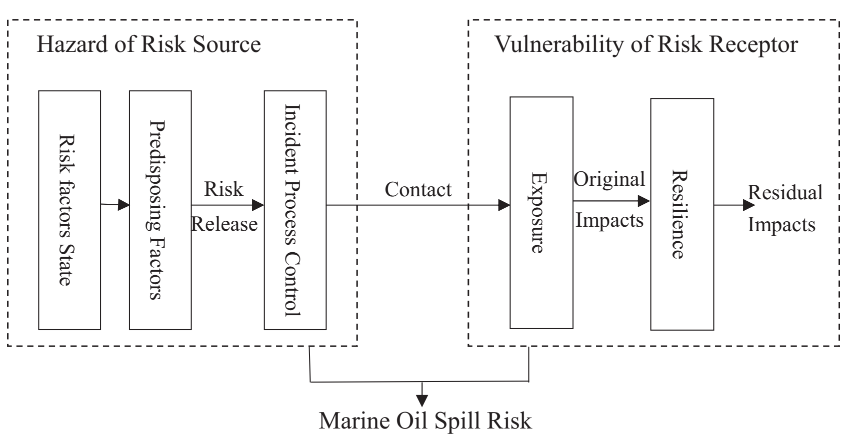

Fig. 1. Conceptual system of marine oil spill pollution accident risk.

Table 2
Empirical models for indexes used in marine oil spill risk mapping.

$R = H \times V$	$H = \frac{H_1 \times H_2}{H_3}$	$H_1 = 0.6 \times 0.5(H_{11} + H_{12}) + 0.4 \times 0.5(H_{13} + H_{14})$
		$H_2 = 0.2(H_{21} + H_{22} + H_{23} + H_{24} + H_{25})$
		$H_3 = 0.5(H_{31} + H_{32})$
	$V = \frac{V_1}{V_2}$	$V_1 = \sqrt{0.5(V_{11} + V_{12}) \times 0.5(V_{13} + V_{14})}$
		$V_2 = \sqrt{V_{21} \times V_{22}}$

of marine oil spill pollution accidents that occurred and the marine oil spill risk system constructed in Section 2.1. Moreover, the equations have been adapted according to high quality empirical data and analysis of the intrinsic mechanisms in marine oil spill risk system. For example, risk factors state (H_1) is determined by the external factors including condition of wharfs (H_{11}) and level of technical equipment (H_{12}), and the internal factors including dispersion of channel (H_{13}) and distance of oil reserve bases (H_{14}). However, the intrinsic factors (H_{11} and H_{12}) are more important than the external factors (H_{13} and H_{14}) to the risk factors state, so have a higher weight. Hazard of risk source is directly proportional to risk factors state (H_1) and predisposing factors (H_2), and inversely proportional to control state (H_3). Vulnerability of risk receptor is directly proportional to exposure (V_1), and inversely proportional to resilience (V_2).

The marine risk measuring procedure involves three steps. Firstly, qualitative and quantitative data is obtained of the indexes in the parameter layer for each unit. The parameter layer indexes are ranked by four grades according to their characteristics and valued by 4, 3, 2, and 1 respectively. With the normalized quantitative values of the indexes of parameter, the indexes in medium 2 are estimated by the models (Table 2). Secondly, the indexes in medium 1 are estimated using the corresponding models with the normalized qualitative values of the indexes in medium 2. Finally, the risk of marine oil spill is described by multiplying hazard and vulnerability referencing the other risk characterization (Varnes, 1984; Lan et al., 2009; Liu et al., 2010, 2013).

2.4. Study area and data source

Dalian is an important port city and a base for petroleum refining. Recently, with the increasing number of oil tankers, the probability of marine oil spill has also increased. The building of 300,000 dwt crude oil terminal of Dalian new harbor and Changxing Island, Petrochemical Park in Changxing Island and chemical industry park in Songmu Island and the other petrochemical projects in building or building in planning all increase the marine oil spill risk of the maritime area of Dalian. Moreover, the region contains the nature reserve of spotted seals, bathing beach of Xinghai Park and the coastal tourism resort of Fujiazhuang, which are hypersensitive to oil spill, and once an oil spill pollution accident occurred, the damage is huge.

The coastal areas of Dalian were divided into eight districts to assess the marine oil spill risk. Relevant data and information were collected in accordance with the index system constructed above. Wind speed, wave height, tidal velocity, biodiversity, and biomass were obtained by the monitoring data during 2010–2011. The social information was derived from statistics provided by the local government authorities. The information about the state of risk source and control measures was obtained from Maritime Safety Administration and Harbor Bureau of Dalian. The other data and information of vulnerable receptor were extracted using GIS tools.

17 parameter layer indexes for each unit were normalized according to the Table 3. The indexes were ranked into one, two, three, and four, and then graded by values of 4, 3, 2, and 1 respectively. Values for indexes in the medium layer were calculated on the base of the parameter layer indexes by the models given in the Section 2.3. Finally, the values of marine oil spill risk were calculated for all eight units.

3. Results

The value ranges of the indexes H, V, and R are $0.25 \leqslant H < 16$, $0.25 \leqslant V < 4$, and $0.06 \leqslant R < 64$, respectively. Values of hazard, vulnerability, and risk were calculated using the MOSRM approach for all the eight districts in Dalian, which is shown in Table 4. The coastal area of Dalian was divided into zones at high risk ($R \geqslant 2.5$), medium risk ($1.5 \leqslant R < 2.5$), and low risk ($R < 1.5$).

3.1. High risk zone

In Fig. 2, high risk zones include Lvshun-Laotieshan sea area, Changxing Island sea area, and Dalian bay coastal area, its area is 5588 km^2, corresponding to 32.5% of Dalian coastal area.

Table 3
Normalization of the parameter layer indexes.

Indexes	Rank one	Rank two	Rank three	Rank four
Condition of wharfs H_{11}	Petroleum wharf	Bulk terminal or container wharf	Passenger wharf	No wharf
Level of technical equipment H_{12}	Below domestic average	Domestic average	Domestic advanced	International advanced
Dispersion of channel H_{13}	High density (intersection of channel)	Medium density (more than 4 channels)	Low density (3–4 channels)	Lower density (1–2 channels)
Distance of oil reserve bases H_{14}	<25 km	25–50 km	50–75 km	>75 km
Annual average wind speed H_{21}	>5 wind force	4–5 wind force	3–4 wind force	1–2 wind force
Annual foggy days (visibility less than 1 km) H_{22}	>50 days	31–50 days	10–30 days	<10 days
Average wave height H_{23}	>5 m	3–5 m	1–3 m	<1 m
Duration of ice age H_{24}	>3 months	2–3 months	1–2 months	<1 month
Water depth H_{25}	<10 m	10–20 m	20–30 m	>30 m
Emergency input of sea area H_{31}	High	Medium	Low	Non
Emergency plan of sea area H_{32}	Perfect emergency plan	Reasonable emergency plan	Preliminary emergency plan	No emergency plan
Marine eco-environmental sensitivity V_{11}	Sensitive (spawning ground, coastal wetland, marine protected areas and so on)	Sub-sensitive (scenic spot, marine entertainment area, and so on)	Low-sensitive (industrial water related to human consumption, reserved area)	Non-sensitive (industrial water consumption, port waters)
Coast type V_{12}	Sandy beach	Muddy beach	Rocky beach	Man-made beach
Biodiversity V_{13}	>4	3–4	2–3	<2
Biomass V_{14}	High	Medium	Low	Very low
Tidal velocity V_{21}	>105 cm/s	70–105 cm/s	35–70 cm/s	<35 cm/s
Annual rainfall V_{22}	>800 mm	700–800 mm	600–700	500–600 mm

Table 4
Risk degree and rank of zoning units in coastal areas of Dalian.

Basic unit	Hazard (*H*)	Vulnerability (*V*)	Risk degree (*R*)	Risk zonation
Wafangdian coastal area	1.04	1.68	1.74	Medium risk area
Changxing Island sea area	1.82	1.76	3.2	High risk area
Jinpu Bay	1.21	1.5	1.82	Medium risk area
Lvshun-Laotieshan sea area	1.91	3.37	6.43	High risk area
Dalian Bay coastal area	2.21	1.24	2.75	High risk area
Huayuankou-Pikou sea area	2.15	0.57	1.23	Low risk area
Changhaixian sea area	2.24	1.08	2.42	Medium risk area
Zhuanghe coastal area	1.77	0.61	1.09	Low risk area

Lvshun-Laotieshan sea area has the highest degree of risk with high hazard and high vulnerability. There are complex channels and Lvshun Port. The high biodiversity, Laotieshan Nature Reserve and Lvshunkou scenic area contribute to high vulnerability. The Changxing Island sea area and Dalian Bay coastal area are also high risk zones, both of which have the 300,000 dwt crude oil terminal, longer ice age and larger waves. Moreover, Dalian bay coastal area has an oil reserve base and Changxing Island sea area has nature reserve of spotted seals.

The suggestions for the high risk zone are: (1) regional planning of port channel to avoid the collision of oil tankers; (2) monitoring the oil pollution near the oil reserve bases and improved the emergency responded services to the oil reserve bases; (3) strengthening early warning of bad weather, and avoiding the transporting work of tanker in storms, foggy days, and other bad weather; (4) developing regional emergency plans and input; (5) building professional team of oil removal; and (6) upgrading the equipment in the wharfs.

3.2. Medium risk zone

The medium risk zones are concentrated in Wafangdian coastal area, Jinpu Bay sea area and Changhaixian sea area, the total area is 10,207 km^2, which account for 59.4% of Dalian coastal area. The high-density channel, close to the oil reserve base, more foggy days and richer biodiversity contribute to higher degree of risk of Changhaixian sea area. Wafangdian coastal area has higher risk because of longer ice age, shallower waters and richer biomass. There are rich biomass and tourist resort in Jinpu bay sea area.

The suggestions for medium risk zone include: (1) reducing the oil tankers navigating in the shallow waters; (2) the new site wharfs could avoid the sensitive seas such as the areas with rich biomass, high biodiversity, nature reserve; (3) improving regional emergency response procedures.

3.3. Low risk zone

The low risk zones are concentrated in Huayuankou-Pikou sea area and Zhuanghe sea area, its area is 1379 km^2, corresponding to 8.1% of Dalian coastal area. The low risk zones not only have low-density channel, deep waters but also have the higher resilience of ecological system. There are some scattered wharfs in Huayuankou-Pikou sea area and Zhuanghe sea area, which are suggested to union or discard in reasonable planning. The local government officials should also pay more attention to the emergency plan and input on marine oil spill pollution accidents.

4. Discussion

A risk system for marine oil spill pollution accidents has been constructed, which is more special than the environmental and natural disaster risk system (Yang et al., 2006; Lan et al., 2009; Shi, 1996) due to the complexity of the marine ecosystem, the fuzziness of the boundary, and the limitation of the marine knowledge. The system is composed by risk source and risk receptor. Risk

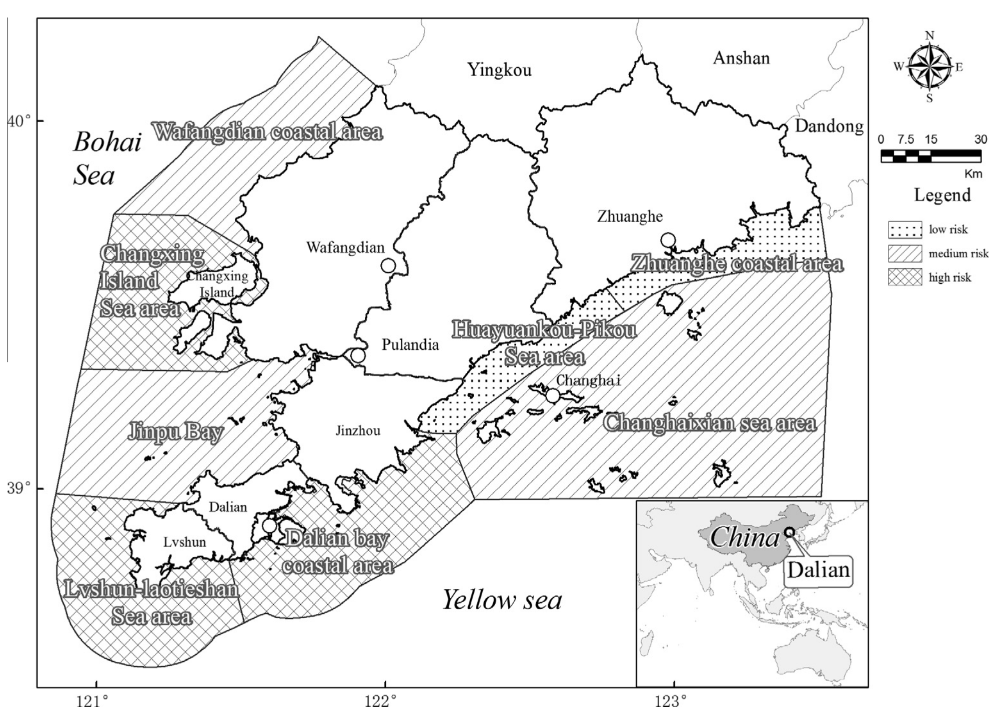

Fig. 2. Risk mapping of marine oil spill in coastal areas of Dalian.

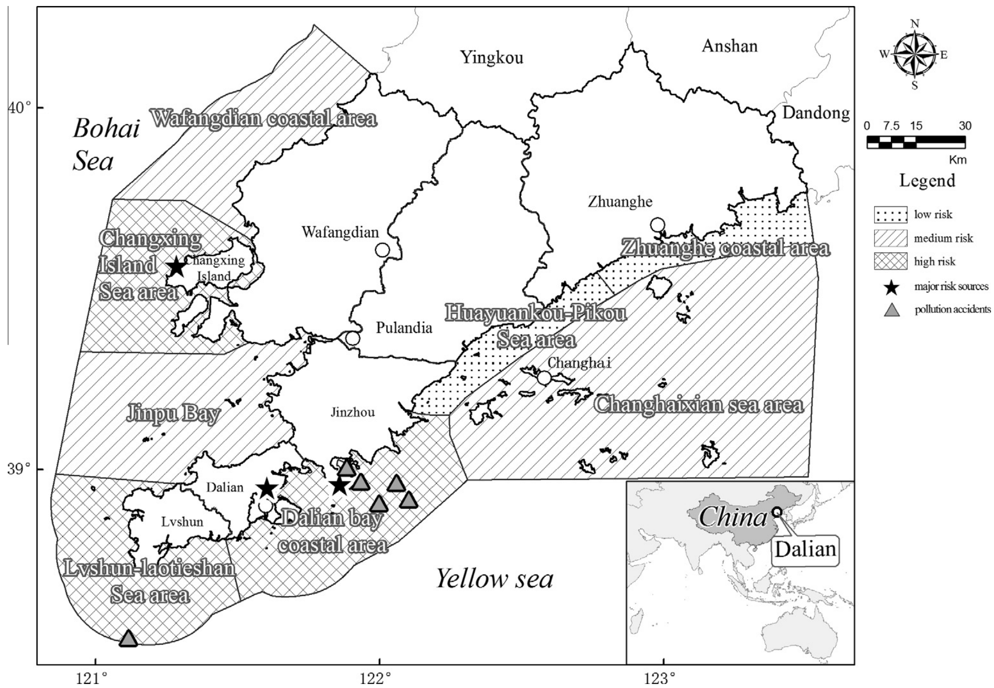

Fig. 3. Mappings of marine oil spill pollution accidents (2004–2014), major marine oil spill risk sources and risk level for the coastal areas of Dalian, China.

source presents a sufficient condition for the risk and risk receptor is the necessary condition to enlarge or reduce the risk. Moreover, a complete index system for marine oil spill risk mapping has also been proposed on the base of the risk system. The index system includes 17 indexes in four layers, with 11 sub-indexes related to hazard of risk source and 6 sub-indexes related to vulnerability of risk receptor. The mapping index system is more effective and operable than the previous systems (Olita et al., 2012) because it considers the availability of data, all the hazard factors, the sensitive receptors and the regional control measures of risk management. There are some differences between the risk indexes for marine oil spill pollution accidents and for natural disasters or environmental pollution accidents. The control measures for hazard reduction of marine oil spill pollution are more important because the marine oil spill accident pollutions have many human-induced factors, however, the natural disasters are difficult to control and mitigate. The receptors in marine oil spill accidents are mostly stationary which cannot be transported once the accidents occurred. However, the receptors in environmental pollution accidents are relatively movable (for example people can be transported). Therefore, in marine oil spill pollution accidents, hazard mitigation is very important because human mistakes and weather conditions are the main reasons for the marine oil spill pollution hazards. More precise indexes need to be derived from the further analysis of more case studies.

The paper discusses the models used to measure the risk, hazard, vulnerability and the relationship of factors in the marine oil spill risk system. These models are constructed according to the actual interactions between the factors in marine oil spill risk system by analyzing the accidental oil spill cases and expert judgment. The upper index is determined by the sub-indexes using multiplication, division or addition according to the real relationship among them. The resulting risk maps are accurate and applicable to large-scale coastal areas because the normalization methods used for parameter layer indexes and the ranking ranges for risk degree.

The coastal area of Dalian, China was used to demonstrate the effectiveness of the MOSRM approach. Unfortunately it is difficult to validate the precision of the marine oil spill risk mapping. Although, the sample number of marine oil spill pollution occurrence is small in a statistical sense, we examined the accuracy of the MOSRM approach based on a comparison between the risk mapping results and the distribution of the marine oil spill pollution occurrence histories in Dalian coastal areas. There are only 6 marine oil spill pollution accidents occurred in 2004–2014 as reported (gained from local marine oil spill accident reports), and Fig. 3 shows the distribution map of the accidents occurred and major risk sources. It can be seen that the accidents all occurred in high risk zones and the three major risk sources are all located in high risk zones. The results may have some coincidence due to the few data, but the official feedback (by discussion with officials of Dalian City Oceanic and Fishery Administration and Maritime Safety Administration and Harbor bureau of Dalian) has also confirmed that the resulting risk map is consistent with the actual risk distribution and the local government decision-making, and provides an important base for oil spill risk management. However, further evidence is needed to validate the approach.

5. Conclusion

This paper has outlined the details of the Marine Oil Spill Risk Mapping (MOSRM) approach at the scale of a coastal city. The approach involves construction of a risk system for marine oil spill pollution accidents, development of a mapping index system, evaluation and calculation of the risk indexes, and marine oil spill risk mapping. The mapping indexes are appropriate and complete because they are derived from the causal risk system. And measurement model incorporated the non-liner dependences between the risk factors. Finally, the approach was applied in the case of Dalian coastal area to demonstrate the effectiveness, and Dalian coastal area was divided into high, medium and low risk zones. The resulting risk map is consistent with the actual risk distribution and the local government decision-making according to the discussion with officials of Dalian City Oceanic and Fishery Administration and Maritime Safety Administration and Harbor bureau of Dalian. The specific countermeasures for each unit should offer important base for marine oil spill risk preventing and management in Dalian.

Further analysis of typical marine oil spill accidents and more information is still needed to improve the mapping indexes and the measurement model. The robustness could be evaluated by considering to apply the MOSRM approach to several different coastal areas, but this is outside the scope of this paper and will be pursued in future.

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