Journal of Hazardous Materials 171 (2009) 471–477

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

# The economy of oil spills: Direct and indirect costs as a function of spill size

Xin Liu [a,*], Kai W. Wirtz [b]

[a] YanTai Institute of Coastal Research for Sustainable Development, CAS. 264003 YanTai, China
[b] Institute for Coastal Research GKSS Centre, 21501 Geesthacht, Germany

ARTICLE INFO

*Article history:*
Received 22 January 2009
Received in revised form 5 June 2009
Accepted 7 June 2009
Available online 16 June 2009

*Keywords:*
Oil spill simulation
Spill costs
Economic assessment method

ABSTRACT

As a rational basis for addressing both ecological and economic consequences of oil spills, a combination of simulating and estimating methods is proposed in this paper. An integration of the state-of-the-art oil spill contingency simulation system OSCAR$^{TM}$ with economic assessment method leads to realistic oil spill scenarios including their biological and economic impacts and the effort taken for combat as well as to an estimate for the total oil spill costs. In order to derive a simple function of total costs depending on few spill characteristics such as size, a number of hypothetical scenarios are simulated and evaluated for the German North Sea area. Results reveal that response costs of per unit oil spilled as well as integrated costs of oil released are simply characterized as two particular power-law functions of spill size. Such relationships can be straightforward transferred into decision making for efficient prevention and combat strategy in the study area.

## 1. Introduction

In the world oceans, more than 100 million tonnes of oil are daily shipped by tankers [1]. The high traffic intensity connected with frequently occurring bad weather conditions, the increasing number of offshore wind farm installations and with always possible human errors still means a real risk for accidents [2]. Accidentally large oil spills usually have a tremendous impact on marine and coastal environments. In order to enhance preparedness and to plan efficient combat strategies, in particular in eco-sensitive regions, an operational estimation of potential impacts and costs caused by oil spills is of paramount importance [3]. However, concurrent spill simulation models often focus on describing key physical and chemical processes that transport and weather the oil on and in the sea [4], tending to leave aside financial consequences of spill [5]. From an economic point of view, combat strategies have to reasonably balance all costs and benefits resulting from the employment of facilities and man-power and lowered impacts on environmental goods. In addition, admissible claims based on the integral cost estimation of an oil spill are of great interest for various parties including local stakeholders, state and federal governments and responsible parties [6,7]. In recognition of these problems detailed pre-spill studies are sometimes essentially important to define the potential range of impacts and their dependency on major spill characteristics such as the quantity of oil released, weather and current conditions [8]. In the present study we, thus, integrate a classic oil simulation model with a module for cost valuation as shown in Fig. 1. The latter is based on the aggregation of major spill cost categories including response costs (i.e. cleanup costs), environmental damages and socio-economic losses. The coupled spill-cost model is intended to assess how the ecological and economic consequences of oil spills vary with external conditions like weather or spill size [9]. As a reference and basis for statistical analysis, multiple oil spill scenarios are generated for the German North Sea area.

### 1.1. The Pallas oil spill in German North Sea

The German North Sea, and in particular the Wadden Sea, is of an outstanding environmental and economic importance which is reflected by, e.g., the number of protections for coastal habitats and by the number and intensity of resource uses such as ship traffic. Its shallowness and the large intertidal areas, however, make the Wadden Sea also vulnerable to spills [20]. Apart from regularly occurring marine oil pollution in the Southern North Sea, e.g. by illegal oil releases [21], even minor accidental spills can, therefore be rather destructive so that they are of ongoing concern to both pollution control authorities and environmental protection organizations. Awareness has been significantly increased since Nov. 28, 1998, when the burning cargo Pallas stranded two nautical miles off the island Amrum in Schleswig-Holstein, Germany [22]. As a result of the Pallas accident, 60 tonnes of fuel oil were released, causing numerous environmental and economic damages. For example, more than 7300 dead Eider ducks were found [23] and approximately DM 14 millions had been used for cleanup and salvage.

---

* Corresponding author.
*E-mail address:* xin.icbm@gmail.com (X. Liu).

0304-3894/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2009.06.028

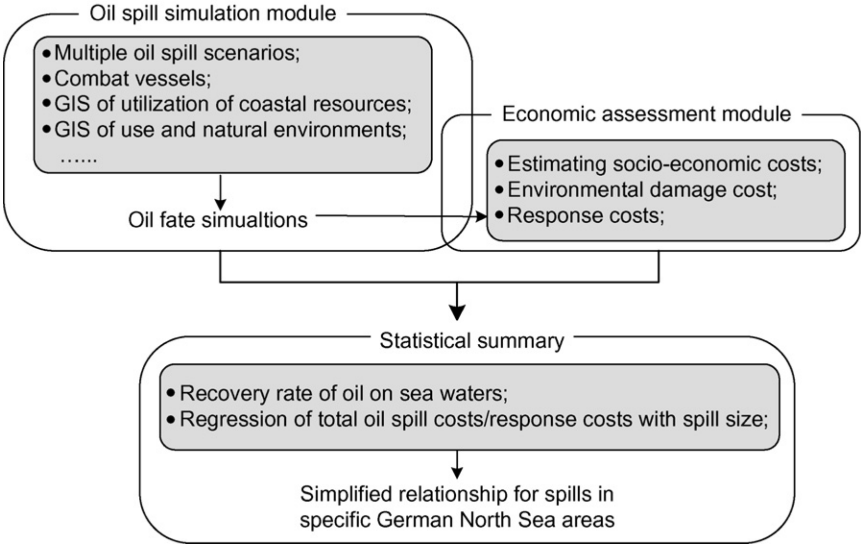

**Fig. 1.** A coupled simulation and economic assessment model presented in this study.

## 2. Description of methodology

### 2.1. Simulation model

In order to estimate the distribution of oil in three physical dimensions over time, the comprehensive OSCAR$^{\mathrm{TM}}$ (Oil Spill Contingency And Response) simulation tool developed by SINTEF, Norway was used [10–12]. The model comprises modules for calculating the three-dimensional transport of oil and its transformation. Transport also includes stranding on shorelines and sedimentation, while for the transformation a variety of processes are resolved, such as slick spreading, evaporation, emulsion and biodegradation. OSCAR$^{\mathrm{TM}}$ quantifies the distribution of a generic pollutant (as mass and area) in various environmental compartments including water surface, water column, atmosphere, sediments or shorelines. This information is linked to calculate mortality of birds (see below). In contrast to most oil models, OSCAR$^{\mathrm{TM}}$ also accounts for the human actions in the aftermath of a spill. The simulation of response activities based on a multi-agent component allows for the parameterisation of rule-based containment activities such as removal from the water surface, transport and storage or the spread of dispersant chemicals [13,14]. As a consequence, the duration of utilizing pre-defined recovery facilities during a combat scenario can be calculated. Wildlife mortality induced by oil contamination is directly proportional to probability of death by oil pollution, species density in habitat selected and area swept by oil slicks. The area swept by oil is calculated for the habitats occupied by the species of concern in the simulation model [15].

### 2.2. Potential oil spill costs

#### 2.2.1. Environmental damages

Oil spills lead to a degradation of natural resources and, consequently, to a decrease of their services in the aftermath of an incident. The lost services is represented by the time-integrated area $L$, which can be estimated in terms of the fraction $f(t)$ of intact services which is a time-dependent recovery function [16–18] to describe the potential services of injured habitats [18]. Hence, the loss of services during the year $t$ after the spill is $1-f(t)$. $L$ sums over $b$ years of loss until the injured resource is completely restored:

$$L = \sum_{t=0}^{b} (1 - f(t)) \left( \frac{1}{1+d} \right)^{t} \tag{1}$$

$d$ is the yearly discount rate reflecting that the present service losses are more costly than the future ones. In NOAA [19] a value of $d = 0.03$ is recommended. The lost value ($V$) of a specific affected habitat or population, respectively, is:

$$V = M \cdot Q \cdot L \tag{2}$$

where $Q$ denotes the total amount of units injured resource and $M$ is monetary value per unit resource and year. Often, one has to consider a number (here $n$) of resources damaged by the released oil or chemical. This leads to the total value lost ($T$) which aggregates over individual losses related to each resource,

$$T \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} M_i \cdot Q_i \cdot L_i \tag{3}$$

#### 2.2.2. Socio-economic losses

The pollution after an oil spill is concerned by a variety of interest groups, in particular those consisting of economic users such as fishermen and hotel owners. As they all suffer from monetary losses. Generally, such losses consist of income losses and property damages. Both of these issues contribute to an integral part of the third party claims in an admissible compensation scheme. The income losses take reduced profit in various economic sectors such as fishery and tourism into account. Like a contaminated natural resource, the affected economic sectors also need time to recover from the oil pollution. Their economic losses (EL) are the sum of foregone incomes during their recovery period:

$$\mathrm{EL} = \sum_{i=1}^{n} yr_i \cdot \sum_{t=0}^{p_i} (1 - f_i(t)) \cdot \left( \frac{1}{1+d} \right)^{t} \tag{4}$$

where $\mathrm{yr}_i$ is the yearly revenue for economic sector $i$, $f_i(t)$ represents the relative percent of service provided by the affected sector $i$ at year $t$ following the incident, $d$ denotes a yearly discount rate and $p_i$ quantifies the required period in years for a full recovery.

#### 2.2.3. Response costs

The response costs (RC) mainly cover the removal of oil from the coastal waters by bringing response equipments into spill location and mobilizing crews. Only mechanical containment and recovery are assumed in oil fate and impact simulations due to restriction of using chemical dispersants in German North Sea areas. Therefore, ultimate cleanup costs (i.e. response costs RC) can be estimated

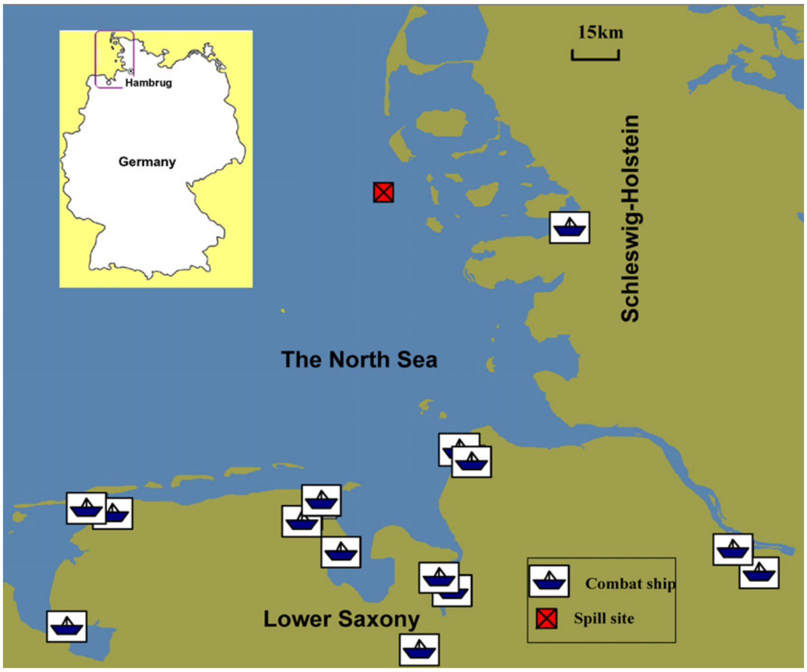

**Fig. 2.** Case study in the German North Sea area. Totally, there exist 14 combat vessels distributed in selected coastal administrative districts.

simply by adding up all costs of cleaning facilities including vessels and labours. The latter can be calculated as the product of the unit price for a specific facility and their duration of using as follows,

$$\mathrm{RC} = \sum_{j=1}^{n} \mathrm{up}_j \cdot \mathrm{du}_j \tag{5}$$

Where $\mathrm{up}_j$ is unit price for combat vessel *j* and its crews, which can be obtained from the national department of water and ship management, Germany; $\mathrm{du}_j$ represents duration of facilitating combat vessel *j*.

### 2.2.4. Spill scenarios

Referring to the Pallas case, multiple spill scenarios were simulated by OSCAR. The bathymetry of the study area shown in Fig. 2 have been included from depth grid database in OSCAR [24], while maps of environmental habitats and biological information of breeding area of birds have been compiled on the base of German North Sea environmental survey [25].

As the Pallas case demonstrated that Eider ducks are most susceptible to oil contamination, they are here taken as exemplary species representing the diverse wildlife in the study area. This choice simplifies the analysis and provides a rather conservative measure of ecological oil spill impacts. Eider duck abundances range from a few hundred to 2000 birds per km$^2$ in the reference region [26]. Note that the strong seasonal variation with higher abundance during the autumn is typical for a series of migratory birds while the low winter values are typical for local bird populations.

Wind fields were generated by a meteorological model [27]. Three-dimensional hydrodynamic data representing the large spatial variability as well as vertical variability of currents in German North Sea area were imported from a regional model [28] and Surface water temperature and salinity are close to realistic expectations.

The air immediately above the water was assumed to have the same temperature as the water surface [15]. All data cover 12 monthly periods ranging from January to December 2001. In order to cover a spectrum of possible scenarios, for each month a spill of heavy fuel oil M-100 with six different sizes from 7 to 2200 tonnes were simulated, giving rise to totally 72 (6 × 12) cases of oil pollution. Each simulation was run for up to 25 days.

Along the German North Sea area, there exist 14 combat vessels distributed in selected coastal administrative districts (see Fig. 1). Based on those available combat vessels, each scenario extrapolates the impacts of oil spill under realistic conditions, also taking feasible response strategies into account. All aspects of the response activities, e.g. the number of recovery ships, the arrival times and the equipment specifications are stated close to available technical information. For all spill intensities, the time needed to deploy combat facilities on waters is assumed to be equal and be within 2 h. Oil recovery strategies of individual ships are defined as a set of rules to search for the nearest, oldest and thickest oil patches within a given geographical area.

For each scenario the mass balance of the crude oil droplets in various environmental compartments such as water surface, shoreline, atmosphere, sediments and so on, the polluted area within economic zones and within different environmental habitats including habitats of bird species are quantified. In addition, the number of activated response vessels, their corresponding operation times as well as quantities of recovered oil on waters are recorded, respectively. In order to estimate wildlife impacts, a fixed fraction of birds in polluted area is assumed to die based on the probability of encounter with the oil slick [15].

Finally, the total oil spill costs are estimated for each of 72 scenarios separately. Total costs comprise response expenditures, environmental damages and economic losses. Table 1 summarize the oil spill costs model input parameters for all scenarios. Expenditures for individual combat vessel, falling into the interval of €300 to €1620/h are obtained from the Federal Ministry of Transport, Building and City Development, Germany. Environmental damages include the loss of use and non-use value or passive value of damaged waters, beaches and birds. In order to enhance the validity of the evaluation results, we transferred conservative per unit values of damaged environmental resources obtained from a previous work [29], in which a few hundred of research works are analysed for estimating lost welfare of the same or similar environmental resource. Direct economic losses are estimated on the base of

**Table 1**
Major parameters and their values used in spill cost model.

| Parameter | Description | Value |
|---|---|---|
| *f*(*t*) | Time-dependent recovery function | A *S*-shaped smooth transition ranging from 0% to 100% |
| $M_i$ | Monetary value per unit resource *i* and year | [a]$M_{beach}$ = €379200/km$^2$/year<br>[a]$M_{water}$ = €26100/km$^2$/year<br>[b]$M_{duck}$ = €62.5/bird |
| $yr_i$ | Yearly revenue for economic sector *I* | [c]$yr_{fishery}$ = €568.8 Millions/year<br>[d]$yr_{tourism}$ = €2250 Millions/year |
| $up_i$ | Price of using facility *i* per hour | [e]*i* = {combat vessel \| Neuwerk, Mellum, Eversand, . . . . . ., Knechtsand, Marcus}; $up_i$ ranges from €300/h to€ 1618/h |

[a] Costanz et al. (1997).
[b] Frech-McCay (2004).
[c] Germany fishery products annual (Lieberz, S. M. and Ramos, K., 2003).
[d] The economic productivity at the German coast (Hagner, 2003).
[e] Water and ship management, Federal Ministry of Transport, Building and City Development, Germany. http://www.wsv.de.

forgone income from tourism and fishery. For the quantification of recovery duration, different assumptions are made. Given large spills over 700 tonnes, we expect that recovery of environmental habitats lasts more than one year and for small and middle size spills environmental recovery durations are assumed to vary between one and six months. While, economic sectors are assumed to be recovered within 6 months. The variation of economic recovery for both small spills, middle and large spills is taken as relatively small, as these economic activities such as fishery and tourism are often driven by market forces.

To examine the efficiency of combat strategies, two indicators are calculated, i.e. combat costs per tonnes (*CCT*) and oil recovery ratio (*ORR*). The former is determined through a division of oil response costs by a sum of recovered oil (e.g., response costs/total amount of oil spilled) and the latter quantifies the fraction of the pollutant (e.g., oil) being removed from the waters by physical means (e.g. quantities of recovered oil/total amount of oil spilled).

## 3. Results and discussions

### 3.1. Fate of oil

The model simulated the weathering processes of the released 'oil particles' and their interactions with the coastal area. Simulation results reveal that after the oil immerged into the water column, evaporation and dispersion start immediately. Sedimentation and stranding process highly depend on factors including persistence of oil, hydrodynamic forces, meteorological conditions and the efficiency of cleanup responses. If the weather and technical equipment allow an efficient oil removal and offshore winds prevail, sedimentation and stranding may even lag for several days after the spill. Hence, having adequate combat strategies and a good knowledge of spill trajectories are critically important in order to protect sensitive coastal regions. In addition, all scenarios indicate a high temporal variability in particular of weathering processes. Namely, the percentage of oil evaporation, of oil submerged in the water column, of oil decayed and of oil reaching the coast (i.e. stranded), etc. is changing over time. In Fig. 3 an example of simulation demonstrates the varying relative importance of removal and transformation processes taking place after a spill of 700 tonnes heavy oil in November. The major part corresponding to 572 tonnes of oil (e.g., 81.7%) is recovered by combat vessels on waters. Residues remain on seas and undergo a number of physicochemical transformations into different forms of carbohydrates, also within different physical compartments. The percentage of evaporation tends to be stable in a very short time period, because of low volatility of heavy oil. Other processes including degradation, sedimentation and stranded tend to increase as time goes on.

The model predicted fatalities of Eider ducks according to polluted residence area as well as abundance of duck species. A large variation of mortality was found across all scenarios regardless of spill size. That is, there is a weak relationship between spill volume and number of sea birds killed as addressed by Burger [30]. In the case of a large oil spill (700 tonnes), impacts on bird fatalities range from a few hundred to nearly 6100 birds with an average of 2014, as shown in Fig. 4. Generally, mortality is much less if the spill occurs in the first half of the year other than the second of the year, while the two worst scenarios are oil releases in September and November, respectively. The lower impact in winter and spring can in part be attributed to prevailing winds drifting the oil slick offshore and to partly less abundance of Eider ducks in the breeding area during this period.

### 3.2. Recovery on waters

The most influential variable determining the efficiency of response activities on seas are combat costs per tonnes (*CCT*) and oil recovery ratio (*ORR*). As obvious from Fig. 5, the *ORR* increases significantly as spill size increases. For small spills, value of *ORR* is on average only 37%, while an average of 77% is calculated for larger spills over 220 tonnes. This could be explained by the fact

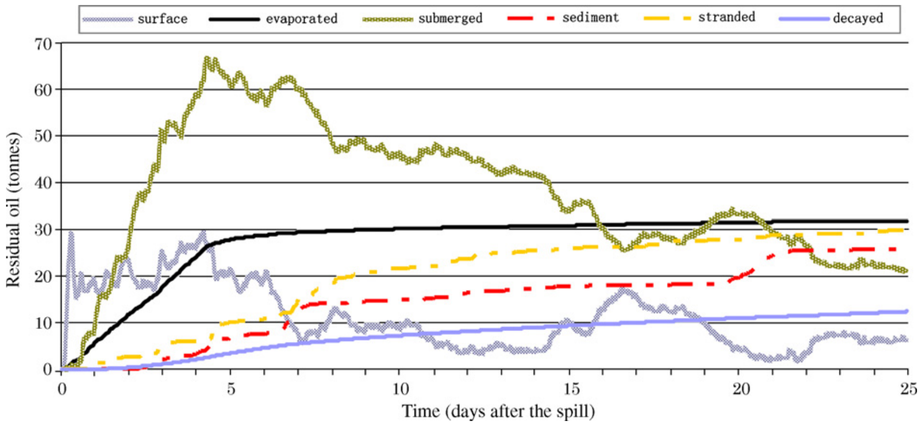

**Fig. 3.** Simulation of weathering and removal processes including the use of mechanical recovery responding to a hypothetical release in November (site 54°32.5′; 8°17.24′; spill amount: 700 tonnes).

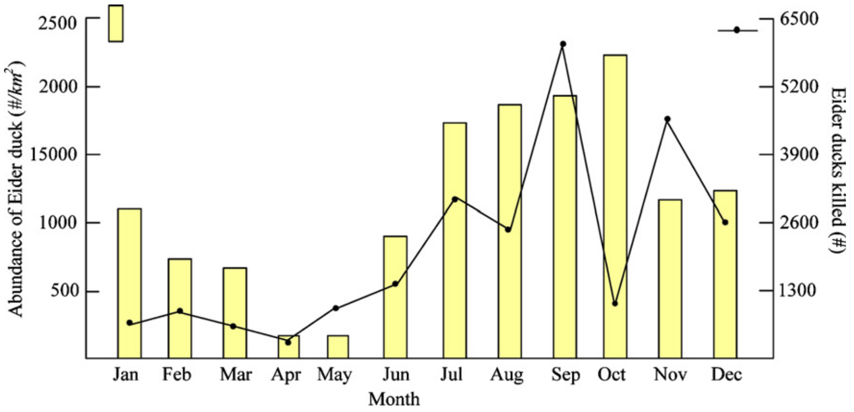

**Fig. 4.** Eider duck population densities in breeding areas within the German North Sea area across months for 1992 are represented by histogram (Adapted from [26]). Dots with continued line were used to describe simulated Eider duck mortality caused by oil pollution within 700 tonness of heavy fuel oil spilled in different months over a year.

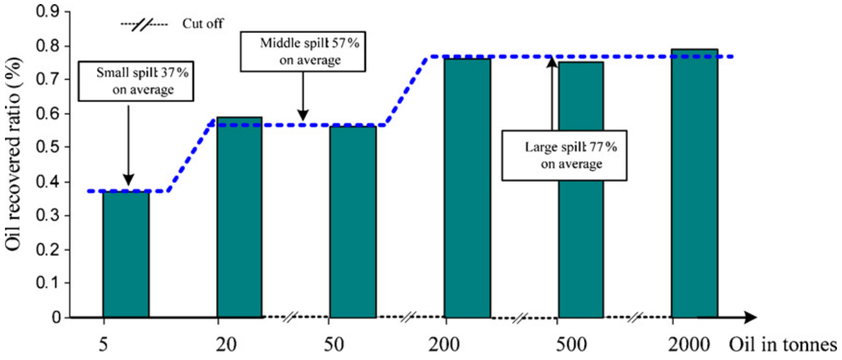

**Fig. 5.** The relationship between the oil recovery ratio and the spill size.

that the small spills are much easier to be dispersed by winds and currents. This makes the collection of oil on waters more difficult. Hence, the option of "leaving for natural cleaning" can be recommended for very small spills ($\ll$7 tonnes) under extreme weather conditions. In contrast to *ORR*, per ton costs of spill response (*CCT*) increases significantly as the spill size decreases (see Fig. 6). The log–log regression of mean combat cost per ton against amount of spilled oil ($t$) revealed an unequivocally power-law relationship as follows, with an overall good performance of the regression model reflected by $R^2 = 0.9862$.

$$Log(CCT) = -0.9507 * Log(t) + 15.387$$

This demonstrates again that compared to the small spills, responses to large spills are more cost effective, and again supports the view of "leaving for natural cleaning" in the case of very small spills from an economic view.

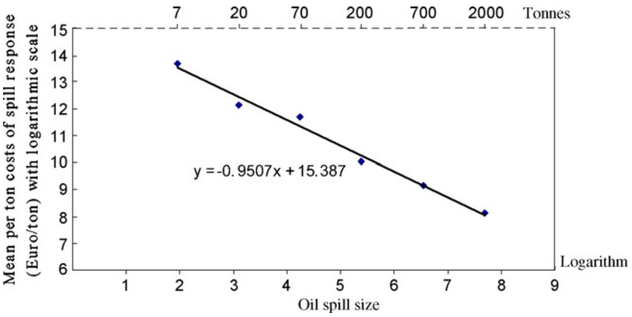

**Fig. 6.** Regression between specific spill response costs (per tonnes) and spill size.

### 3.3. Total oil spill costs

For each of all simulated scenarios, total oil spill costs aggregate its three individual cost categories including response costs, environmental damages and economic losses. For all 72 scenarios, total oil spill costs range from €1.28 to €41.27 millions, which corresponds to 0.0021% of the German GDP measured at market prices for the year 2006. The impact of the spill size ($t$) as an independent factor on the total spill costs (*TC*) again follows a log linear relation (Fig. 7) as follows,

$$Log(TC) = 0.4667 \cdot Log(t) + 13.894$$
$$R^2 = 0.9036$$

For further validation, this relationship is applied to results presented in previous studies. Among a total of 68 incidents, [8] reported 2 heavy fuel oil spill incidents in Germany, the Ondina and

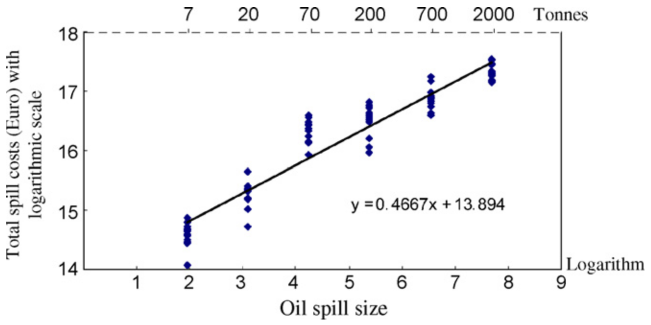

**Fig. 7.** Total costs (*TC*) versus spill size ($t$). The individual data derive from 72 scenario calculations made for the German bight area which are fitted by a power-law function (cont. line).

the Brady Maria spills, respectively. In 1982, the Ondina, spilled 300 tonnes of oil leading to a total cost of $11.5 Millions when referred to its 1997 value, while in 1986, merely 2.34 Millions (1997 US$) were claimed for 200 tonnes released by the Brady Maria. In our study the total economic costs of a spill of 300 tonnes in the Ondina was estimated to €15.94 Millions, which is comparable magnitude with expenditures reported by [8]. Corresponding to the 200 tonnes spill of Brady Maria, the total spill cost of €12.8 Millions was approximated by using our specific power-law function. However, the author noted that no environmental damages were included in the cost estimate, because the environmental damage as an admissible claim was only discussed to be introduced potentially to the international oil spill compensation program in the world after the disaster of Exxon Valdez, 1989. A neglect of environmental damages obviously leads to an underestimation of total spill costs. Moreover, compared with findings by [31] that DM 14 Millions was used for towing the spilled vessel and cleanup, our response cost of nearly €6 Millions estimated by the specific power-law function presented in Fig. 5 is consistent.

Undoubtedly our regressions of direct and indirect costs over spill size are reasonable compared with previous studies. These findings will help predictions of economic consequences after severe oil pollution. It should be noted that neither complete removal of every slick of oil is technically achievable in practice nor a huge of effort and money expended in relation to a very small amount of oil are reasonable. The results can be further used to judge whether or not a particular planned activity is appropriate. If spills were to occur in the German North Sea area in the new future, for instance, modelled response costs should be weighted against potential spill damages, which is a difference between modelled total spill costs and response costs. Cost effectiveness derived should then be taken as one of important considerations to determine whether a course of combat action is an improvement on doing nothing and allowing natural processes to take their course [32].

The balance of resource usages and habit protection along the German North Sea coast is representative for a variety of coastal zones worldwide. In addition, response costs per unit effort should also be in the same order of magnitude for other regions. As a consequence, those predictions can be reasonable for a wider range of sites.

## 4. Conclusions

In this paper an economic assessment method is coupled with three-dimensional oil spill simulation model, which also describes direct response measures. The work provides an objective measure relating the potential and, above all, a relatively complete magnitude of pollution depending on simple spill characteristics. It may be further applied, more generally, in oil spill management, environmental risk assessments or, more specifically, for cost-benefit analyses of combat programs where investments into combat facilities and prevention have to be compared against possible cost reductions in likely accident scenarios. For the economic assessment, not only socio-economic losses but damaged natural resources resulting from oil pollution are taken into account. The results show that total oil spill costs range from €1.28 Millions to €41.27 Millions, highly depending on spill size, weather conditions and ecological importance of the area polluted by oil. When we use the most conservative value of €1.28 Million (scenario with lowest damage for 7 tonnes of heavy oil spilled), for instance, any recommend changes to law or investment on advance mechanical containment, less than €1.28 Millions targeting to prevention or recovery of 7 tonnes of oil can be clearly approved.

Of course, any model-based estimate is inferior to real cost data. It is noted the socio-economic losses estimation does not address seasonally varying details. However, the usage of modelling techniques enables the generation of a well-defined series of scenarios. By defining a clear frame of reference, this series enables the identification of straightforward relationships between key characteristics such as spill size and total costs or recovery cost and ratio. We suggest that these functions can be to some extent transferred to other sites or types of spill in German North Sea area and can, thus, be valuable for environmental impact assessment and decision making related to coastal contingency planning.

## Acknowledgements

We thank SINTEF Marine Environmental Technology for the permission to use the OSCAR software. This work was supported by the National Natural Science Foundation of China (NSFC) with a grant number of 7080152, ShanDong Natural Science Foundation (#2008BS09012), China and the third sub-project in a CAS innovation program numbered with KZCX2-YW-224. The authors would like to thank Dr. Johanna Staneva for providing wind and current data as well.

## References

[1] J. Rodrigue, C. Comtois, B. Slack, The Geography of Transportation, Routedge, New York, 2006, p. 284.
[2] Biervliet, K., Roy D. and Nunes, P.A.L.D., 2006.An accidental oil spill along the Belgian coast: results from a CV study. Report #41.2006. International Energy Markets.
[3] Vethamony, P., Sudheesh, K., Babu,M.T., Jayakumar, S., Manimurali, R., Saran, A.K., Sharma, L.H., Rajan, B. and Srivastava, M., 2007. Trajectory of an oil spill off Goa, eastern Arabian Sea: Field observations and simulations. Environmental Pollution, in press.
[4] M. Reed, Ø. Johansen, P.J. Brandvik, P. Daling, A. Lewis, R. Fiocco, D. Mackay, R. Prentki, Oil spill modeling towards the close of the 20th century: overview of the state of the art, Spill Science & Technology Bulletin 5 (1999) 3–16.
[5] K.W. Wirtz, N. Baumberger, S. Adam, X. Liu, Oil spill impact minimization under uncertainty: evaluating contingency simulations of the Prestige accident, Ecological Economics 61 (2007) 417–428.
[6] X. Liu, K.W. Wirtz, Total oil spill costs and compensations, Maritime Policy & Management 33 (2005) 49–60.
[7] D. Heltonnes, T. Penn, Putting response and natural resource damage costs in perspective, in: the Proceeding of International Oil Spill Conference, 8–11 March, Seattle, USA, 1999.
[8] C. Grey, The cost of oil spills from tankers: an analysis of IOPC fund incidents, in: Proceedings of the International Oil Spill Conference, The International Tanker Owners Pollution Federation Limited (ITOPF), Seattle, USA, 7–12 March 1999.
[9] I.C. White, F. Molloy, Factors that determine the cost of oil spills, in: International Oil Spill Conference 2003, Vancouver, Canada, 6–11 April 2003, 2003.
[10] Aamo, O.M., Reed, M., Dahling, P.S., Johansen, Ø., 1993. A laboratory-based weathering model: PC version for coupling to transport models. Proceedings of the 1993 Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, pp. 617–626.
[11] O.M. Aamo, M. Reed, A. Lewis, Regional contingency planning using the OSCAR oil spill contingency and response model, in: Proceedings of the 20th Arctic and Marine Oil Spill Program, AMOP Technical Seminar, Vancouver, Canada, 1997.
[12] K. Dowing, M. Reed, Object-oriented migration modelling for biological impact assessment, Ecological Modelling 93 (1996) 203–219.
[13] M. Reed, O.M. Aamo, P.S. Daling, Qnantitative analysis of alternative oil spill response strategies using OSCAR, Spill Science and Technology 2 (1995) 67–74.
[14] Reed, M., Frenceh, D., Rines, H. and Rye, H., 1995b. A three dimensional oil and chemical spill model for environmental impact assessment. Proceeding of the 1995 International Spill Conference, pp.61–66.
[15] D. French-McCay, J.J. Rowe, N. Whittier, S. Sankaranarayanan, D.S. Etkin, Estimation of potential impacts and natural resource damages of oil, Journal of Hazardous Materials 107 (2004) 11–25.
[16] Penn, T., Tomasi, T., 2002. Environmental assessment: calculating resource restoration for an oil discharge in lake Barre, Louisiana, USA. Environmental Management 29, 691–702.
[17] D.P. French McCay, J.J. Rowe, Habitat restoration as mitigation for lost production at multiple trophic levels, Marine Ecology Progress Series 264 (2003) 233–247.
[18] R.W. Dunford, T.C. Ginn, W.H. Desvousges, The use of habitat equivalency analysis in natural resource damage assessments, Ecological Economics 48 (2004) 49–70.

[19] NOAA, 1999. Discounting and the treatment of uncertainty in natural resource damage assessment. National Oceanic and Atmospheric Administration Damage Assessment and Restoration Program.

[20] C. Van Bernem, T. Luebbe, Oil at sea—catastrophes and long-term effects, Wissenschaftliche Buchgesellschaft, Darmstadt, 1997, p. 177.

[21] Fleet D. M., S. Gaus, E. Hartwig, P. Potel, B. Reineking & M. Schulze Dieckhoff 1999. PALLAS-Havarie und Seevogelsterben dominieren Spuelsaumkontrollen im Winter 1998/99—Oelopfer in der Deutschen Bucht im Zeitraum 1. Oktober 1998 bis 31. Maerz1999. Seevoegel (20) 79–84.

[22] B. Reineking, The Pallas Accident, Wadden Sea Newslettter, 1999.

[23] Fleet, D.M. & B. Reineking. Have efforts to clean the marine environment been successful? – German beached bird surveys provide an index for oil pollution levels in the southern North Sea. In: Rodriguez, C.R., Brebbia, C.A. (Ed.) 2000. Oil and Hydrocarbon Spills, Modelling, Analysis and Control II, WIT Press, Southamptonnes, Bostonnes, pp. 117–126.

[24] M. Reed, M.K. Ditlevsen, B. Hetland, M. Gersea, I. Durgut, B. Hoverstand, K. Skognes, Ø. Johansen, H. Rye, MEMW User Manual. SINTEF Applied Chemistry, Marine Environment Technology, Norway, 2003, p. 94.

[25] Rasmussen, L.M., D. M. Fleet, B. Hälterlein, B.J. Koks, P. Potel, P. Südbeck, 2000. Breeding Birds in the Wadden Sea in 1996—Results of a total survey in 1996 and of numbers of colony breeding species between 1991 and 1996. Wadden Sea Ecosystem No. 10. Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Joint Monitoring Group of Breeding Birds in the Wadden Sea. Wilhelmshaven, Germany.

[26] J. Kohlus, H. Kuepper (Eds.), Umweltatlas Wattenmeer. Landesamt fuer den Nationalpark Schleswig-Holsteinisches Wattenmeer, Umweltbundesamt Stuttgart, Ulmer, 1998, p. 270.

[27] Staneva, J. (2004) Numerical modeling of the German Bight. 1. GETM Users Workshop, Baaring Hojskole, Denmark.

[28] Stanev, E.V.; Gemein, N.; Staneva, J.; Badewien, T.; Wolff, J.-O.; Reuter, R.; Flemming, B. (2006, solicited) Downscalling dynamics and sediment dynamics from regional to coastal: The East-Frisian Wadden Sea. Geophysical Research Abstracts, Vol. 8, 08786 2006, EGU Joint Assembly, Vienna, Austria, 02–07 April 2006.

[29] R. Costanza, R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Suttonnes, M. van den Belt, The value of the world's ecosystem services and natural capital, Nature 387 (1997) 253–260.

[30] Burger, A. E. (1993) Estimating the mortality of seabirds following oil spills: Effects of Spill Volume. Marine Pollution Bulletin, 26(3), 1993, pp. 141–143.

[31] G. Clauss, M.A. Amro, Oelunfallbekaepfung bei Tankerkatastrophen, 54, Technical University International, 2003, pp. 8–13.

[32] Purnell, K. J., 1999. Comparative costs of low technology shoreline cleaning methods. International Oil Spill Conference. Seattle, USA.