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Integrated modeling of oil spill response strategies: a coastal management case study

Xin Liu *

Yantai Institute of Coastal Zone Research, CAS. 264003 Yantai, China

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ABSTRACT

Oil spills are commonly considered as one of the worst forms of marine pollution. Often they constitute a challenge for an operational contingency management, since an oil spill contingency management encompasses multiple and often conflicting objectives and has to face various sources of uncertainty. Focusing on a well-documented case, the Pallas oil spill in Germany, the selection of optimal strategy among others is formulated as a multi-criteria decision-making problem that involves various environment, socio-economy and management related effects. These effects may not be directly comparable and compatible due to the fact that they are measured in multiple metrics. To solve such a multi-criteria decision-making problem, this paper proposes monetary evaluation models to assess performances of using different response strategies. Combined with the benefit cost analysis and the cost effectiveness analysis, this method enables to further determine the favored and rational strategy and the worthwhile investment of using combat facilities, respectively. Through the case of Pallas, such a proposed method is demonstrated as an important decision-making support tool in the domain of coastal zone management.

1. Introduction

Oil spills are commonly considered as one of the worst forms of marine pollution, having serious impacts on coastal activities and marine life (Ventikos and Psaraftis, 2004). For instance, the oil tanker Exxon Valdez spilled an estimated 11 million gallons of crude oil across 1300 miles of coastal line in Alaska in 1989 (Williams and Olaniran, 1994), causing the damage estimated at 2800 million US dollars. In the case of Prestige in the year of 2002, the costs in cleaning alone have amounted to 1 billion Euros. The response to an oil spill emergency in an effective way hence turns out to be an imminent concern in the domain of integrated coastal zone management (Douligeris et al., 1995; Galt, 1997).

The task of evaluating the response strategies is necessary but complex (Iakovou et al., 1997). It is necessary because it help decision-makers to select an optimal strategy which aims at lowering response costs and keeps the drifting oil away from sensible coastal areas (Liu and Wirtz, 2005). This task is also complex because it needs to consider both the environmental and socio-economic consequences following the using of proposed combat strategy for the oil spill. Conventional methods of multi-criteria analysis can be used as a decision support tool to deal with the data through a weighted linear aggregation (Almasri and Kaluarachchi, 2005). Often the environmental and socio-economic effects might not be directly comparable and compatible with each other due to the fact that they are measured in different metrics. In other words, the multi-criteria analysis is less favored if these effects are non-linearly related. Additionally, determining relative weights between effects is a subjective process and often requires a priori knowledge (Chen et al., 2004a; Brown et al., 2001). These and other issues of conventional multi-criteria analysis motivate seeking for alternative decision

* Tel.: +86 535 2109195; fax: +86 535 2109000.
E-mail address: xin.icbm@gmail.com.
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support techniques that are capable of integrating these effects in an effective way.

This paper proposes monetary evaluation models combined with spill simulations as a decision-making support tool for an oil spill contingency management. It focuses on the lost values of the injured environmental habitats and economic sectors affected by the accident. They integrate several stages as they are applied, one may

- select the least costly scenario by estimating the total oil spill costs which aggregate the combat costs, environmental damage costs and economic sectors' income losses;
- determine the most efficient response strategy by using the benefit cost analysis;
- examine the worthiness of additional investments in the response strategies through the cost effectiveness analysis.

The paper is organized as follows: in Section 2, we simulate a hypothetical oil spill and various response strategies including the using of the combat vessels based on the Pallas accident. In Section 3, monetary evaluation method is described in great detail, in particular, its potential advantages in overcoming the above limitations of multi-criteria analysis. Finally, in Section 4, the performances of different combat strategies are evaluated by using the proposed method. Section 5 concludes the paper.

2. The Pallas accident

On 28th November 1998, the burning cargo ''Pallas'' stranded two nautical miles off the island Amrum in Schleswig-Holstein, Germany (Reineking, 1999). As a result of the Pallas, vast amounts of fuel oil through a tear in the damaged ship hull after the stranding were released to the surface of the German North-Sea area, which has been declared as a major part of Wadden Sea PSSAs (particularly sensitive sea areas) within the framework of the International Maritime Organization (IMO) due to its ecological sensitivity, social, cultural, economic importance and scientific and educational purposes. For example, the PSSAs host important breeding populations of seabirds, seals, dolphins and other marine species and are also a particularly important tourist zone. Other nearby activities comprise of fishery, transportation and some offshore wind farming practices. The yearly gross value of its economic productivity (over 125 billion Euros) is among the highest in Germany, although the North-Sea coastal region in Germany shown in Fig. 1 is relatively small.

However, frequented shipping movements with millions of tons of cargo transferred annually make this zone vulnerable to oil or chemical spills, as demonstrated by the ecological disaster caused by the Pallas oil spill. Over 20,000 birds, mainly Eider ducks are affected, which demonstrates that such an oil spill together with its long-lived consequences poses one of the major episodic threats for near-shore ecosystems and the human use of the coastal areas. Approximately, 7 million Euros were used for clean-up and salvage following the accident. Referring to the Pallas case, a hypothetical oil spill, in which totally 60 tons of fuel oil spill at the site where the Pallas occurred (54°32.5′N; 8°17.24′E), is simulated by OSCAR (oil spill

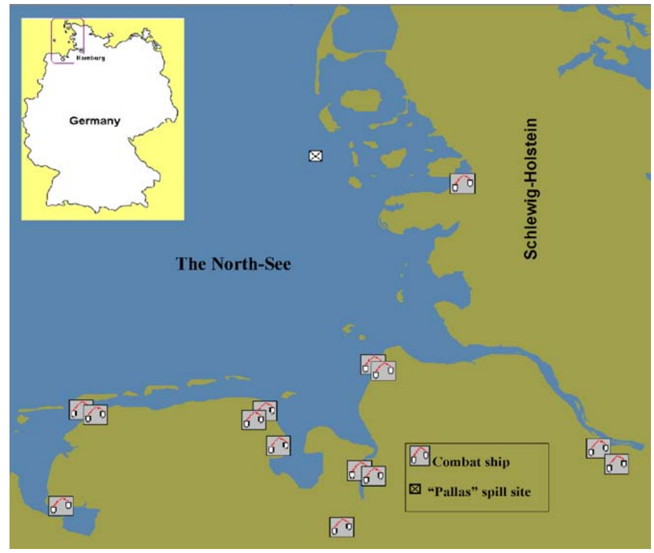

Fig. 1 – German North-Sea case study area. Totally, there exist 14 oil combat vessels distributed in selected coastal administrative districts along the German North-Sea area.

contingency and response), a model system developed by SINTEF, Norway (Reed et al., 1995, 2004; Aamo et al., 1996; Daling et al., 1990). By using the actual information for wind and currents, OSCAR provides a 3-dimensional projection of the temporal evolution exhibited by the oil. In accordance with observations (Clausen, 2003), the affected area is in the simulation limited to the east part of the German North-Sea coast or, more specifically, the Schleswig-Holstein coastal area (see right graph in Fig. 2). Obviously, a number of environmental resources and economic activities are threatened by an oil spill. With special attentions paid to oil pollution, six (e.g. three economic- and three environmental-related) criteria shown in the left diagram of Fig. 2 are selected to be considered. They reflect existing interests as well as background information at the German North-Sea coast but may to a larger extend also reflect the situation in many other coastal regions around the world. For simplicity, the environmental damages are represented in terms of the polluted beaches, coastal waters and affected habitats of exemplary bird species. Here, the latter only refer to eider ducks, since November is the month with the highest number of this species (about 100,000 birds) in the Schleswig-Holstein coastal area (Reineking, 1999). The socio-economic losses include the clean-up costs (e.g. the costs for using the combat vessels and their facilities) and income losses of fishery and tourism. It is estimated that the yearly incomes for fishery and tourism amount to 568.8 million and 2.25 billion Euros in this region, respectively (Lieberz and Ramos, 2003; Hagner, 2003). Geographical distributions of both human uses (mostly fishery and tourism) and natural breeding areas of eiders in the Schleswig-Holstein are highlighted in the right graph of Fig. 2.

OSCAR provides a variety of scenarios and each scenario extrapolates the impacts of feasible response strategies based on available combat vessels (see Fig. 1). Their characteristics and collection rules-of-thumb can be described by the model system in great detail. One major issue of the discussions in

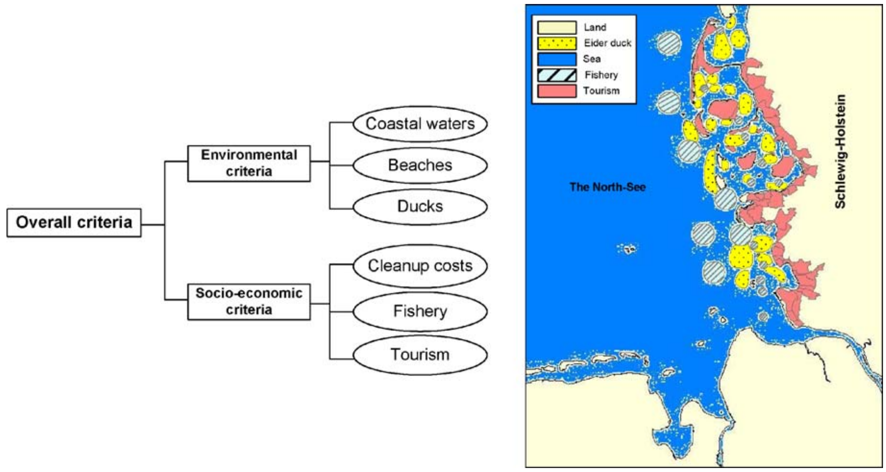

Fig. 2 – Criteria selected in the case study. Left: a hierarchy diagram of selected criteria. Right: geographic distribution of environmental habitats and human use in the affected coastal areas.

Table 1 – Performance matrix of scenarios of using different response strategies. Bold numbers indicate the minimal effects in terms of the specific criterion among the scenarios.

	Scenarios				
	Sce.1	Sce.2	Sce.3	Sce.4	Sce.5
CC (€)	951,756 (Alt.1)	1,101,615 (Alt.2)	1,072,185 (Alt.3)	1,047,811 (Alt.4)	485,083 (Alt.5)
B (km^2)	0.1074	**0.0946**	0.1047	0.0977	0.1205
CW (km^2)	0.1978	**0.1707**	0.1925	0.1815	0.2255
F (km^2)	**0.0029**	0.003	0.0032	**0.0029**	0.0036
T (km^2)	**0.0034**	0.0036	0.0036	0.0045	0.0043
D (birds)	156	**133**	148	141	174

Notes: CC (clean-up costs): the costs in Euros of using the combat vessels and their equipments; B (beaches): the covered beach area (km^2) by stranded oil; CW (coastal waters): the polluted coastal water in km^2 by oil; F (fishery): the polluted fishery area (km^2); T (tourism): the polluted tourism area (km^2) in main recreational area along the German North-see coastline; D (duck): summed amount of dead eider ducks.

the aftermath of the accident was whether an appropriate number of response ships are in existence and, if yes, how many of these should have been used in the Pallas case. Thus, combat vessels are randomly selected in the simulations. According to the simulations, the ratio between quantity of recovered oil from waters and the total number of combat vessels used to be examined to determine initially which combat scenarios are relatively efficient. After a preliminary evaluation of these combat scenarios, five different combat alternatives were pre-defined so that they cover a reasonable spectrum of ship stocking. A description of these scenarios in which different combat alternatives are facilitated are summarized in Table 1, which synthesizes the OSCAR results for each scenario in different respects (e.g. the performance matrix of combat strategies). In total, five combat vessels are used in the first response strategy (e.g. Alt.1). They are Neuwerk, Mellum, Westensee, Knechtsand and Norderhever. On the basis of Alt.1, the Alt.2, 3 and 4 has one more different combat vessel, respectively and the Alt.5 has only four combat vessels used in the Alt.1. Table 2 details the five alternatives.

Table 2 – Response strategies and their descriptions.

Alternatives	#	Name of vessel
Alt.1	5	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee
Alt.2	6	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Nordsee
Alt.3	6	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Eversand
Alt.4	6	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Thor
Alt.5	4	Neuwerk, Mellum, Knechtsand, Norderhever

3. Estimating environmental and socio-economic damages

Conventional method of the multi-criteria analysis can be used to deal with the above performance matrix through a linearly weighted aggregation of the criteria in each scenario (Wirtz et al., 2004, 2006). Due to the fact that the quantitative measurements in the performance matrix are expressed in multiple metrics, they are not easy to be directly comparable and compatible with each other. In other words, it is not

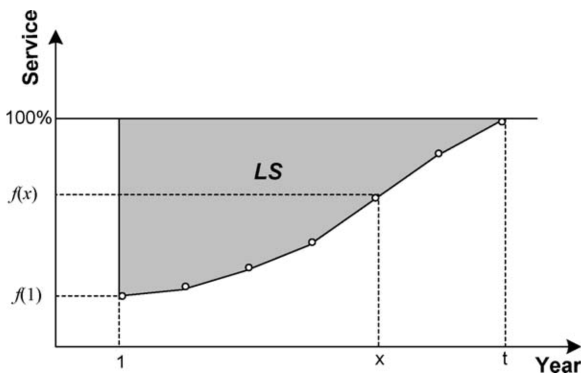

Fig. 3 – Lost services and S-shaped time-dependent recovery function. *t* is the year when the injured habitat is fully recovered. *f*(*t*) is the service in percent provided by the injured habitat in the year *t*.

suitable to integrate them through a linear aggregation, which is typically used in the multi-criteria analysis. Moreover, determining relative weights between criteria in the multi-criteria analysis is sometimes less favored, as it requires a priori estimate of relevance attributed to all the criteria. An efficient alternative is to evaluate all damages measured in non-monetary terms economically. Such a monetary evaluation, on the one hand, breaks complex pollution effects in multiple metrics down to a single value in money terms. On the other hand, it intuitively provides both the public and managers the effects of environmental problems by using money as an indicator.

3.1. *Calculating environmental damages*

Oil spills lead to a degradation of the nature resource since they decrease their services during the year following the incident. Fig. 3 schematically illustrates the recovery path of an injured habitat over time. In the *x*th year following the incident the damaged habitat is supposed to be able to provide only $f(x) \times 100\%$ of its full services. Hence, the loss of services during the *x*th year is $1 - f(x) \times 100\%$. Ultimately, the habitat is completely recovered in the *t*th year and generates again a full service. The total lost services (*LS*) due to the oil spill can be estimated as,

$$LS = \int_{x=1}^{t} (1 - f(x)) \left(\frac{1}{1+d}\right)^{x-1} \quad (1)$$

where *f*(*x*) is a time-dependent recovery function (Penn and Tomasi, 2002; French McCay and Rowe, 2003; Dunford et al., 2004) to describe the potential services, which the injured habitats could provide in the *x*th year following the accident. The lost services are represented by the time-integrated area (*LS*) as shaded in Fig. 3. An example of the usefulness of the lost services can be seen in Appendix A. There exist many shapes of recovery functions, for example, the linear, S-shaped and logistic. The S-shaped recovery path as shown in Fig. 3 seems more realistic, since from an economic view, its marginal services that the injured habitats provide at the first year (e.g. Year 1) following the incident and at the full restoration year (e.g. Year *t*) are expected to be close to zero. Through examinations of effects of different recovery functions on the estimations of lost services, we found that the lost service estimations are not sensitive to those different recovery functions, if the recovery time required is not more than 10 years. As long as the recovery time turns larger, their effects become distinct increasingly. The yearly discount rate *d* emphasizes the present service losses are more costly than the future ones. A recommended value of 0.03 is used in NOAA (1999). The lost value (*V*) of a specific habitat injured by the incident is:

$$V = M \times Q \times LS \quad (2)$$

where *M* is the monetary value of one unit natural resource per year; *Q* gives the total area of an injured natural resource. *LS* is the lost services due to the oil spill. It can be determined by Eq. (1). If the injury is primarily to one certain type of animal, the above formula can be simplified to,

$$V_a = M_a \times Q_a \quad (3)$$

where M_a is the price per animal and Q_a is the total number of dead animals. Often a wide range of resources are damaged due to the oil spill, the total environmental value (TEV) damaged by oil spill is given by a simple aggregation as follows,

$$\text{TEV} = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} M_i \times Q_i \times LS_i \quad (4)$$

3.2. *Calculating socio-economic losses*

Income losses are not avoidable when economic sectors such as the fishery and tourism are hit by the oil. Like the environmental resources, the injured economic sectors also need time to recover. The socio-economic losses here focus on the aggregated and discounted income losses IL of different economic sectors over their recovery periods,

$$\text{IL}_i = \text{YI} \times \frac{A_i}{TA_i} \times \sum_{t=1}^{T_i} f_i(t) \left(\frac{1}{1+d}\right)^{t-1} \quad (5)$$

For a specific economic sector *i* with yearly income YI_i, A_i and TA_i quantify the polluted area and the total areas used for the economic sector *i* in the affected region, respectively. $f_i(t)$ is the recovery function and T_i is its specifically required recovery time span. The total socio-economic losses (TIL) is the sum of income losses from all individual economic sectors as follows,

$$\text{TIL} = \sum_{i=1}^{n} \text{IL}_i \quad (6)$$

An example to calculate economic losses due to the oil spill can be seen in Appendix A.

4. Results and discussions

In this section, each scenario as the consequence of using the specific combat strategy to respond to the hypothetical accident is evaluated by the monetary evaluation method mentioned above. Two examinations are made in this section. One is related to investigation of the net present values for each of the combat alternatives to robustly differentiate the optimal and worst combat alternatives among others. The other aims to identify the worthiness of additional investments in the combat alternatives. In the following paragraphs, all of these will be addressed.

4.1. Total oil spill costs

In this present case study, the total oil spill costs (TC) consist of the environmental damages (TEV), economic income losses (TIL) and clean-up costs (CC),

$$TC = TEV + TIL + CC \tag{7}$$

To apply the monetary evaluation models to estimate the total oil spill cost, recovery time required by both the injured habitat and economic sectors are pre-defined in three different periods: the short-term (e.g. 1 year), middle-term (e.g. 5 years) and long-term (e.g. 10 years). The unit price for beach and coastal waters are taken as €115/m^2/year and €21/m^2/year transferred from a global valuation work by Martínez et al. (2007), respectively. With a consideration of both use and non-use values of environmental habitats, these values often represent a very low bound of the economic value of those environmental capital. Value per Eider duck is defined as €62.5 according to French McCay et al. (2004). Clean-up costs mainly cover the removal of oil from the coastal waters by bringing response equipments into spill location and mobilizing crews. It can be calculated as the product of unit price for a specific facility (i.e., combat vessel) and their operation durations in waters. Expenditures for each individual combat vessel falls into the interval of 300–1618 Euros per hour are obtained from the Federal Ministry of Transport, Building and City Development, Germany (WSV, 2009).

Fig. 4 presents an overview of clean-up costs and the total oil spill costs differentiated according to time horizons for each scenario. Generally, the total short-term costs are ranging from 7.8 million (e.g. Alt.2) to 8.8 million (e.g. Alt.5) Euros and the long-term estimates between 62 million and 79 million Euros. By comparing the total oil spill costs in different scenarios, it is apparent that Sce.2 is the best case leading to least costly effects of the hypothetical spill. In contrast, Sce.5 with one ship dropped tends to be worse to effectively combat the oil spill under consideration as long as the effects of the spill becomes longer lived.

Obviously, the accuracy of the estimations highly depends on the assumptions made. Especially, the unit value for environmental goods remains questionable. In principle, they can be measured by economic valuation methods (Liu and Wirtz, 2004; Liu et al., 2009) or obtained through a benefit transfer from previous studies in which the same or similar environmental habitat was evaluated (Ready et al., 2004; Rozan, 2004). Taking a conservative or less controversial value may guarantee the validity of the estimation results, whichever method is approached to obtain the value of environmental goods. Hence, we transferred conservative per unit values of damaged environmental resources obtained from a highly acknowledged work done by Martínez et al. (2007).

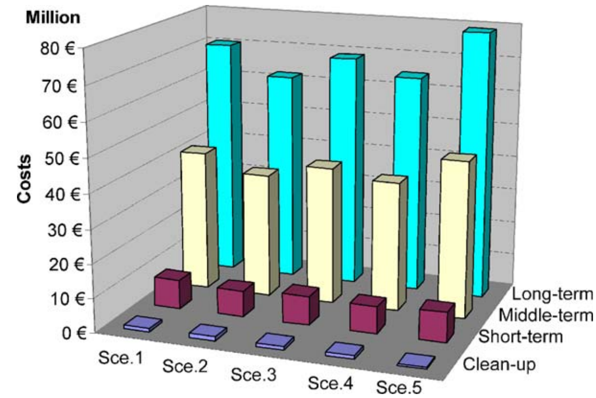

Fig. 4 – An overview of clean-up costs and the total oil spill costs in three different time scales for each scenario.

Additionally, the cost estimation in a short-term scale in Fig. 4 is not sensitive to the manner in which the response strategy is defined. A detailed sensitivity test of these estimations is not discussed here. However, significant differences might arise if more affected criteria are incorporated or a larger oil spill is given, which calls for an elaboration of sensitivity analysis.

4.2. Benefit cost analysis

In order to determine the most effective response strategy, for each combat alternative a benefit cost analysis is applied. This analysis provides a net present value which denotes the difference between the benefit and cost of facilitating the specific combat alternative. Both benefit and cost require a frame of reference which is obtained by simulating the oil spill without any combat measures (i.e., Alt.0). Like the total oil spill cost estimated for each scenario in Section 4, such a reference scenario (Alt.0) results in a different total oil spill cost TC_r for each time horizon. Therefore, the net present value of a specific combat alternative can be derived as,

$$NPV_j = TC_r - TC_j \quad j = 1, 2, \cdots, 5; \; r = 0; \tag{8}$$

Fig. 5 presents net present values in three different time scales for each combat alternative. The highest return in terms of net present value is revealed by the combat strategy Alt.2. Contrarily, Alt.5 gives a lower net present value than other options. Such a conclusion is consistent with the rankings of scenarios mentioned in Section 4.1. Generally, benefits of facilitating response strategy are positively correlated with their costs. However, Alt.3 has lower net present values compared with Alt.4, although it induces higher clean-up costs. Thus, the application of the benefit cost analysis assists decision-makers to identify less rational strategies, which can be ultimately deleted from options or replaced by new strategies.

4.3. Cost effectiveness analysis

Compared with the Alt.5, other alternatives spend different amounts of extra money for facilitating one or two more combat vessels. The worthiness of such investments can be

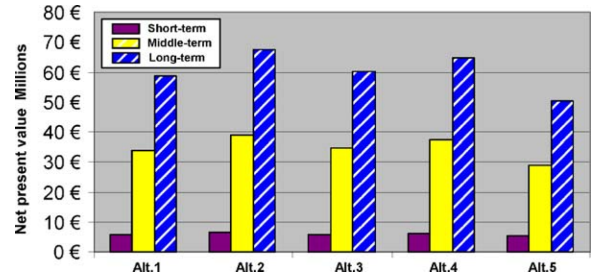

Fig. 5 – Net present values in different time terms for each combat alternative.

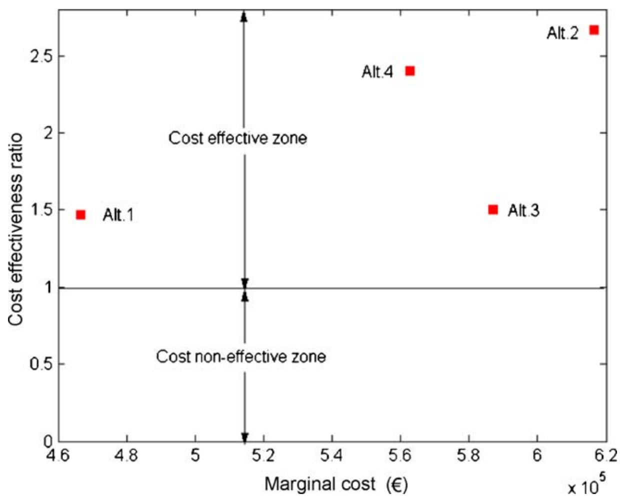

Fig. 6 – Cost effectiveness ration of Alt.1–4 in short-term based on comparisons with the target alternative (e.g. Alt.5).

examined by conducting the cost effectiveness analysis. One key issue in the cost effectiveness analysis is to determine the effective ratio $R_{j,k}$, which is a function of the marginal benefit $MB_{j,k}$ and cost $MC_{j,k}$ between the assessed alternative j and the target alternative k as follows,

$$\begin{cases} MC_{j,k} = CC_j - CC_k \\ MB_{j,k} = NPV_j - NPV_k + MC_{j,k} & j \neq k \\ R_{j,k} = MB_{j,k}/MC_{j,k} = 1 + (NPV_j - NPV_k)/CC_j - CC_k \end{cases} \tag{9}$$

In this case study Alt.5 is taken as the target alternative (e.g. $k = 5$) so that $MB_{j,5}$ is the marginal benefit reflecting the pay-offs of additional investments into combat ships. A cost effectiveness ratio $R_{j,5}$ larger than 1 suggests that such investments are worthwhile compared with maintaining a status quo (e.g. Alt.5). The hypothetical 60 tons of oil spilled falls into the category of small spillages, its possible effects tend to be short-term. Therefore, estimations in a short-term scale are used for determining the effective ratio $R_{j,k}$. As shown in Fig. 6 additional investments for the combat vessels: Westensee and Nordsee in Alt.2 are the most worthy, while Alt.1 and 3 (Westensee and Eversand) tend to be somewhat effective.

However, the result is, of course, very case specific and has to be verified on the base of much more spill scenarios with a variety of spill amounts, a statistical coverage of different meteorological and hydrodynamic conditions.

5. Conclusions

Monetary evaluation model combined with simulation technique is demonstrated here as an important decision-making support tool in the domain of coastal zone management. The combined methodology breaks complex pollution effects measured in multiple metrics down to a single money-term value, which allows these effects to be aggregated in a comparable and compatible way (Braeuer, 2003). In contrast to the multi-criteria analysis, there is no involvement of the weights attributed to the environmental and socio-economic effects in such a monetary evaluation model. It intuitively provides both the public and managers the effects of environmental problems by using money as an indicator. Together with the benefit cost analysis, the coupled methods help decision-makers to identify the most favored and rational response strategy. Additionally, the cost effectiveness analysis provides possibilities to determine a worthwhile investment of using additional facilities in designing a response strategy. Finally, the proposed method may have wider applications in the environmental management, in view of many multidisciplinary and operational studies in which environment–human interactions need to be investigated (Chen et al., 2004b).

Acknowledgments

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Appendix A

To illustrate how such monetary evaluation models might be applied practically, the environmental damages and the income losses are calculated for the scenario 1 shown in the following table in which both the injured environmental habitat and the damaged economic sectors are supposed to be linearly recovered over a period of 5 years. Due to the small footprint of the spill in the fishery and tourism areas, the income losses are estimated relatively low.

	Injured habitat/animal		
	Beach	Water	Duck
Quantity	0.1074 km^2	0.1978 km^2	156 birds
Unit price(€)	115/m^2/y[a]	21/m^2/y[a]	62.5/bird[b]
Lost service by year	1999	100%	100%
	2000	75%	75%
	2001	50%	50%
	2002	25%	25%
	2003	0%	0%
Aggregate, discount losses (€)	29.64×10^6	9.96×10^6	9750
Total (€)	39,609,750		
		Income losses of economic sectors	
		Fishery	Tourism
Polluted area	0.0092 km^2	0.0034 km^2	
Total area	377 km^2	600 km^2	
Yearly income (million/y)	568.8[c]	2250[d]	
Lost service by year	1999	80%	80%
	2000	60%	60%
	2001	40%	40%
	2002	20%	20%
	2003	0%	0%
Aggregate, discount losses (€)	33,590	30,600	
Total (€)	64,190		

Notes: yearly discount rate is 0.03.
[a]Martínez et al. (2007).
[b]French McCay et al. (2004).
[c]Germany fishery products annual (Lieberz and Ramos, 2003).
[d]The economic productivity at the German coast (Hagner, 2003).

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Dr. Xin Liu is an associate professor in the Institute of Coastal Zone Research, Chinese Academy of Sciences. She has developed a number of research interests based around economics and sustainable management including environmental risk assessment; environmental economic valuation; coastal management and decision support systems.