

# Robustness against different implementation of uncertainty in a contingency DSS: the Prestige oil spill revised

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## Abstract:

The dramatic consequences of oil or chemical spills for coastal ecosystems and economic uses make contingency management a politically sensitive task. We here propose a new Decision Support System (DSS) consisting of a combination of modeling and evaluation methods with which different containment strategies can be compared in the light of a variety of potential ecological and economic damages. In this study, the DSS is tested by hindcasting the Prestige accident off the coast of Spain in 2002. In particular, an oil spill contingency simulation model coupled with multi-criteria analysis techniques was used to assess oil spill impacts for weather and current forecasts available at that time. Five different towing directions resulted in many different hypothetical sinking sites which all were simulated separately. Two procedures of including the array of pollution scenarios into the evaluation were considered: the first method uses expected pollution intensities for each towing route, in the second procedure all hypothetical sinking scenarios are rank-ordered so that towing directions are only indirectly compared. Additional uncertainty resulting from incomplete or imprecise information about pollution impact thresholds or different weighting schemes representing major stakeholder groups is also taken into account. We identified clearly one worst option and one or two almost equally well performing routes. For reasonable range limits of evaluation parameters or sinking probabilities, rankings turn out to be robust against the many uncertainties included so far. Even the two different methods of implementing various sinking scenarios did only differ with respect to confidence limits. Robustness as well as transparency of the coupled approach carry a large potential for enhancing the efficiency of decision making even in politically sensitive situations.

**Keywords:** Decision Support Systems, oil spill contingency, multi-criteria analysis.

## 1 INTRODUCTION

One of the major episodic threats for near-shore ecosystems and the human use of coastal areas arise from large oil or chemical spills. Once authorities are informed about an emergency call of an oil carrying transport ship or even a tanker a contingency plan comes into action which often carries various ambiguities. In detail, one has to decide between alternative counter-actions such as removal of surface oil from different locations or usage vs. non-usage of dispersants. Due to the vast array of different environmental and socio-economic impacts, there also exists a multitude of stakeholder groups with di-

verging interests (Komatsu et al. [2003]; Edgar et al. [2003]; Brown et al. [2001]). The growing public demand for environmental responsibility, the fast rise of associated costs and its political dimension call for an early integration of these diverging interests in the process of emergency planning. In principle, this can be addressed by means of a Decision Support Systems (DSS) including a multi-criteria analysis module. Effects of different response solutions can then be projected in time and be evaluated with respect of few aggregated target values. A major difficulty, however, of using DSS based recommendations within the planning process or, more generally, for gaining a high acceptance of the DSS

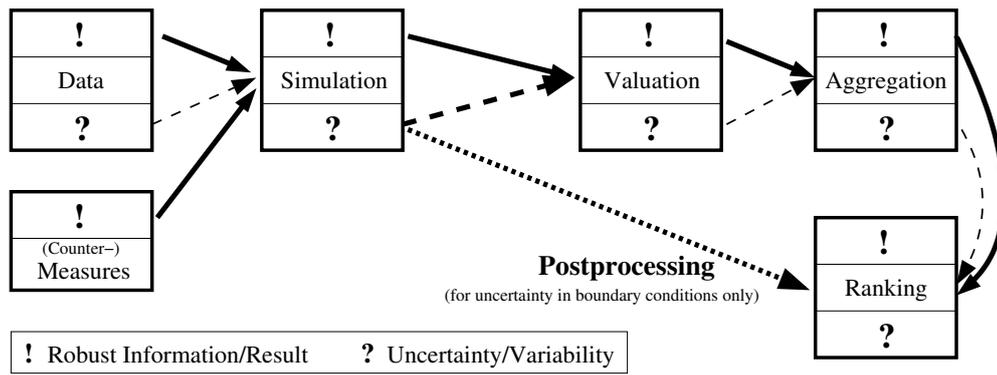


Figure 1: Multi-stage approach for ranking different response measures.

for authorities and stakeholders derive from the uncertainties related to various aspects of the problems such as weather forecasts, presence of endangered seabird populations, evaluation procedures or relative weighting of different factors.

Here, major functionalities of the DSS are outlined comprising the integration of data-sets and response measures into a simulation environment which is further coupled to an economic as well as ecological evaluation scheme. The ranking of different measures results from aggregating the compiled criteria factors in a politically balanced way. The entire scheme is shown in Figure 1. As major parts of this DSS structure were already documented by Baumberger et al. [2004], here only most essential elements of each stage have to be sketched.

This paper sets a particular focus on the effect of including uncertainties in input data or intermediate results. A straightforward approach to reflect incomplete or imprecise knowledge works by a parallel account of diverse scenarios so that the algorithm operates on sets of constellations rather than single values. In the work of Baumberger et al., these variations led to an array of possible results in each stage which are averaged before applying the subsequent operation ("preprocessed uncertainty"). However, due to the nonlinear nature of the following transformations, this procedure, albeit much more simple and elegantly to use, might create a large error. A more precise procedure should maintain the entire variability until the final ranking-stage. Therein, numerous potential consequences of different response options are unfolded and then directly compared ("postprocessed uncertainty", see also Wirtz [2001]). In order to estimate potential quantitative deviations of including uncertainty in different ways into a DSS we here study and contrast preprocessing as well as postprocessing. Both approaches are visualized by the thick dashed lines

in Figure 1.

### 1.1 PRESTIGE SPILL AS CASE STUDY

In order to verify the usefulness of the newly constructed DSS structure, Baumberger et al. [2004] collected a large data-base with essential informations related to the Prestige oil spill. The oil released by the tanker Prestige in autumn 2002 had provoked disastrous consequences along the Spanish and with some delay also French Atlantic coast. In the early phase of the accident, the only feasible combat measure was to tow the ship into different directions. Regional and national authorities had to decide whether to directly face the problem by towing the tanker into a nearby harbor at the Galician coast or to move it to a remote ocean site. Albeit all dragging directions were operable, the uncertainty regarding, e.g., an imminent break-down of the ship seemed to render any rationale judgment of the respective consequences nearly impossible. Hence, a major aim of this paper is to evaluate the potential risks of alternative towing routes and to quantify the discrimination accuracy achievable within the first period of response planning.

## 2 METHODS

### 2.1 SPILL SIMULATION

From the position where the Prestige sent a SOS at 13/11/2002 off the Finisterra cape (42°50N; 09°50W) we defined five towing directions representing the above mentioned different response strategies: North-East (NE), North-West (NW), West (W), South-West (SW) and East (E). Along each towing route 3–13 potential grounding locations were distributed within a maximally three day

trawling range. This yielded a sum of 49 different positions as shown in Figure 2.

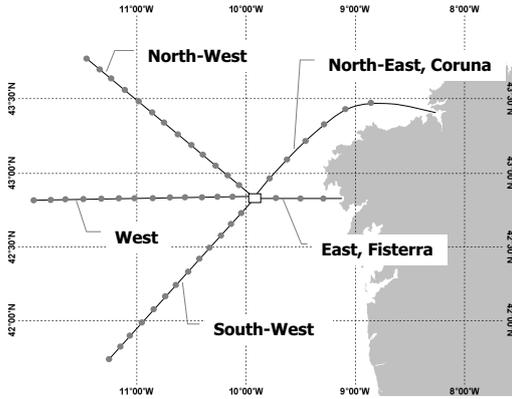


Figure 2: Towing routes and hypothetical sinking positions after 6-hour towing intervals (grey points). It is assumed that the Prestige is dragged at the rate of 32.5 km per day for all directions.

For each potential grounding location the spatio-temporal evolution of spilled oil is hindcasted by the industry standard oil spill simulation and contingency tool OSCAR (Oil Spill Contingency And Response, Daling et al. [1990]; Aamo et al. [1996]). OSCAR projects the distribution of a contaminant controlled by physical transport, chemical-physical transformation processes and by biodegradation. As improvement of most standard oil spill models also a multitude of combat activities such as collecting are simulated in a realistic way using a multi-agent approach. Thus, after including hydrographical and meteorological boundary conditions OSCAR produces reliable estimates of amounts of oil  $P_{jk}$  landed at different coastal areas with index  $k$  within 20 simulation days.  $j$  ( $j = 1 \dots 5$ ) denotes the towing option and is linked to a sub-set of simulations  $S_1, \dots, S_{49}$  addressed by the indices  $n_j$  (e.g.,  $n_j = 1, 2, \dots, 13$  for  $j = 1$ : western route). The number of grounding locations along each route  $j$  can be inferred from Figure 2.

## 2.2 SINKING PROBABILITY

Each grounding scenario  $S_j$  has a specific probability  $p(S_j)$  which depends on the estimated time when the ship is going to break apart. This probability is constructed in two ways. First, it is set constant  $p(S_{n_j}) = p_j$  ( $p_j \leq 1/13$ ). In a second formulation a conditional probability with first increasing and then decreasing values is defined (see

also Figure 3). Also, a more realistic rise of  $p_j$  for the offshore routes is tested since these are characterized by higher waves.

## 2.3 ECONOMIC VALUATION

Many of the affected coastal areas host one of four major resource uses with index  $i$ : fishery ( $i = 1$ ), mariculture ( $i = 2$ ), tourism ( $i = 3$ ) and transport ( $i = 4$ ). Economic impacts are assessed on the base of income losses which in turn are estimated using subregional yearly data for tons of landed fish, harvested mussels, cleared cargo and occupied beds. These impacts are translated to an economic damage indicator  $L_{ij}$  in each sector as a piecewise linear function of the pollution intensity  $P_{jk}$ . If the latter reaches a pollution threshold value  $P_i^*$  the damage equals the regionalized yearly income  $L_i$  as maximal loss:

$$L_{ijk} = L_i \cdot \min \left( 1, \frac{P_{jk}}{P_i^*} \right) \quad (1)$$

The value of  $P_i^*$  reflects both the sensitivity and adaptability of each economic activity (details in Baumberger et al. [2004]). It is hardly possible to confine their exact value so that the analysis is iterated using a set of different  $P_i^*$  (fishery:  $P_1^* \in [5, 10, 15]$ , tourism:  $P_2^* \in [4, 8, 12]$ , transportation  $P_3^* \in [0.5, 1, 1.5]$  and mariculture  $P_4^* \in [0.4, 0.8, 1.2]$ , units:  $10^3$  tons of stranded oil).

## 2.4 ECOLOGICAL VALUATION

Ecological impacts are differentiated with respect to three semi-quantitative indicators for the sensitivity and importance of local habitats: Reproductive capacity, vulnerability and protection level. First, reproductive success of pelagic and benthic populations decreases with the extent of polluted spawning and nursery areas. The latter is assumed to be proportional to the amount of oil reaching estuarine mariculture areas as these mark relevant spawning and nursery grounds. Secondly, on the base of vulnerability indices of Gundlach and Hayes [1978] or Moe et al. [2000], the persistence of oil is estimated using morphological characteristics of the seashore. This value multiplied with  $P_{jk}$  quantifies the aggregated effect of oil on substrates such as sand, rocks, muds or pebbles. Thirdly, a protection factor describes the importance which society attributes to individual coastal areas. In our approach, it depends on the number of protective regulations like, e.g., RAMSAR, EU-Natura 2000 or national Natural Re-

serves, given to an affected area. Again, this factor is transformed to a region and response specific impact score  $L_{ijk}$  by multiplication with  $P_{jk}$ . Like for economic damages, integrating damage scores  $L_{ijk}$  for reproduction ( $i = 6$ ), vulnerability ( $i = 7$ ) and protection ( $i = 8$ ) over all areas  $k$  yield three ecological impact scores  $L_{ij}$ . To account for momentarily not assessable damages of oil remaining on or within the water column after 20 days, these pools are collected into the category "residual risk".

## 2.5 MULTI-CRITERIA AGGREGATION

In order to aggregate all ecological and economic impacts to a single target value of response measures we adopt a Linear Additive Model: for each option, the standardized and weighted performance scores are added up, often along a hierarchical tree (Dodgson et al. [2001]). A negatively sloped linear transformation function is employed ( $T_{ij} = 1 - L_{ij}/L_i^M$ ) to normalize the scores with  $L_i^M$  denoting the maximal impact among all options and  $T_{ij}$  the normalized score for criteria  $i$ . After multiplication of the normalized scores  $T_{ij}$  with weights  $w_i$  expressing the relative importance of a specific criteria  $i$  in a defined decision context we obtain an overall target score for each option  $j$ .

$$T_j = \sum_i w_i \cdot T_{ij} \quad (2)$$

Due to a lack of *a priori* knowledge on preferences in our case study, we define different weighting schemes supposed to be representative for three interest groups involved in the decision making process: fishermen, policy makers and environmentalists (Table 1).

## 2.6 UNCERTAINTY AGGREGATION AND RANKING

In the first preprocessing procedure, variability originating from a non-predictable sinking time of the oil tanker is integrated before the valuation stage. This means that the pollution intensities  $P_{jk}(S_n)$  belonging  $S_1, \dots, S_{49}$  are averaged over each towing route  $j$  using  $p_j$  to calculate an option specific expectation value  $P_{jk} = \langle P_{jk}(S_{n_j}) \rangle$  before applying Equation (1). Having calculated a target value on the base of those averaged pollution intensities for the five response measures, the latter can be rank-ordered. The ranking is then repeated for each distinct combination of minimum, intermediate and maximum threshold value ( $P_i^*$  in Section 2.3) and

for all three weighting schemes (see Table 1). Different outcomes are reduced to a mean rank  $\langle R_j \rangle$  and the standard deviation of option rankings.

In contrast, the second procedure treats each simulation separately so that instead of 5 options 49+2 sinking scenarios are compared. If the ship reaches the Fisterra bight or Coruna harbor, the corresponding pollutions  $P_{jk}(50)$  or  $P_{jk}(51)$  vanish for all areas  $k$  except the respective zone. Again, the ranking of 51 scenarios is repeated for different threshold values and stakeholder profiles. This procedure maintains the dynamics of rankings as potential grounding simulations or harboring cases can be evaluated for every 6h period. The mean scenario specific ranks  $\langle R(S_{n_j}) \rangle$  are finally summed up to an overall ranking for each option:  $R_j = \sum_{n_j} \langle R(S_{n_j}) \rangle \cdot p(S_{n_j})$ .

## 3 RESULTS

Starting from an array of hypothetical grounding locations, OSCAR simulates a variety of different spilling scenarios and coastal damages. Minimum pollution values for each criterion are scattered between different options already indicating a conflict situation for decision makers. The final ranking of 49 sinking and 2 harbor/bight scenarios displayed in Figure 3 reveals that a very early breaking of the Prestige is most disadvantageous. Already after six hours of towing, northern and western towing directions are clearly favored. In the course of the second and third day, dragging the ship into a harbor or bight is assumed to infer low overall damage scores while for ocean-going scenarios the north-western route is ranked best. It provides the highest chance to keep the impact on Spanish coastal areas at a minimum since most of the oil drifts to the Gulf of Biscay.

If sinking scenarios instead of towing routes are directly assessed, i.e. in the case of postprocessed uncertainty, the underlying routes can be ranked as shown in Figure 4. Option E performs best, followed by NW. Clearly, direction SW turns out to be the least valuable response. Although the ranking of options is sensitively affected by the choice of evaluation and weight coefficients, the simultaneous use of three contrasting profiles and pollution threshold values does not level out the discriminating power of the approach (see also Baumberger et al. [2004]). Standard deviations are in general smaller than differences between averaged ranks along routes. Thus, statistically secure distinctions can be made between the best option E, a group of sub-optimal solutions (NW, NE, W) and

Table 1: Three weighting schemes ( $w_i$ ) representing opposing stakeholder profiles.

Profile	Index	1	2	3	4	5	6	7	8
		Fishery	Tourism	Transport	Mariculture	Reproduction	Vulnerability	Protection	Residual risk
Fishermen		0.6	0.1	0.1	0.1	0.025	0.025	0.025	0.025
Policy makers		0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Environmentalists		0.025	0.025	0.025	0.025	0.2	0.3	0.3	0.1

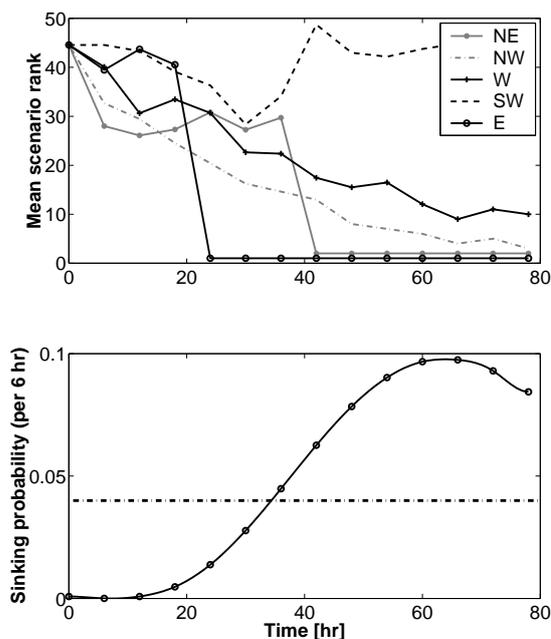


Figure 3: Mean scenario based ranking (“postprocessing”) of different towing options plotted according the sinking time (top). Two alternative versions of the sinking probability are given (lower diagram).

the lowest rank of SW.

This result has also been proven robust against different sinking probability functions as, for example, portrayed in Figure 3. Only extreme low or high values of  $p_j$  could change the rank behavior in a significant way.

In the case of preprocessed uncertainty with a direct ranking of different routes a very similar picture arise (Figure 5, corresponding to the results shown in Baumberger et al. [2004]). Standard deviations in ranks are relatively high so that a clear preference between the best and second best options E and NW is lost.

The ways of how variability enters into the calculation of rankings therefore seem to be of minor im-

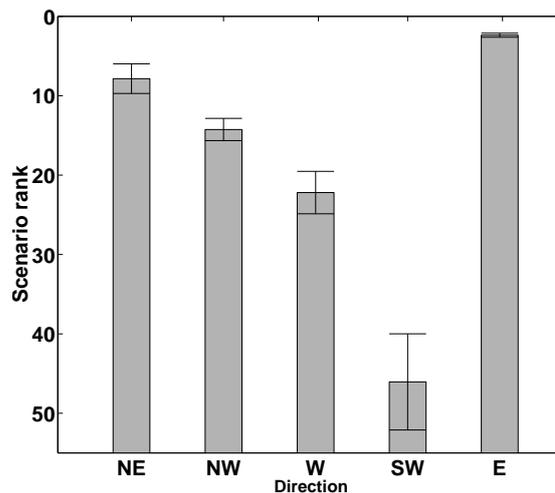


Figure 4: Ranking of the five possible response measures with sinking uncertainty included according a postprocessing mode.

portance. Inherent non-linearities in the multi-stage transformation of pollution values to final rankings is in our study not sufficient to distort the evaluation outcomes.

#### 4 DISCUSSIONS AND CONCLUSIONS

Interestingly, the northwestern towing route of the Prestige as the initial measure taken by the Spanish authorities coincides with one of the best ranked options. However, due to a later turn to the South, the resulting direction SW corresponds to our worst case scenario. This can be taken as an argument to enhance the use of operational DSS in emergency cases as they provide a rational, albeit never perfect base for a fast comparison of alternative countermeasures. A DSS, in addition, allows for testing different containment strategies or oil spill contingency plans in a systematic way.

In comparison to many standard oil spill DSS, the approach presented here includes a multi-criteria

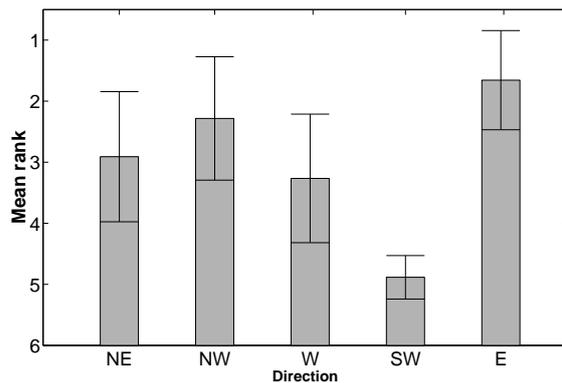


Figure 5: Mean ranking of the five possible response measures with sinking uncertainty included according a preprocessing mode. Standard deviations derive from variations in other insecure parameters.

decision framework with a great variety of both monetary and non-monetary evaluation factors. As it also directly simulates the response measures via the OSCAR module of oil combat, the DSS can be used for optimizing existing containment strategies with respect to a politically balanced target value. Finally, in future applications we aim to refine the definition of the weighting scheme and the values of weight coefficients within a participatory frame. By confronting regional authorities as well as representatives of interest groups with a spectrum of scenarios, the relative relevance of different impacts should be balanced in a more objective as well as interactive way.

As a major result, this study ascertained the robustness of results which a DSS may provide even when relatively few data are available. Uncertainty can be transformed to variability (of simulations and evaluations), leading to the study of large scenario ensembles instead of singular cases. But the final ranking uncertainty as quantified by the standard deviation does not necessarily render a discrimination of response measures infeasible, as often thought by practitioners as well as modelers. In theory, uncertainty aggregation between successive modeling stages may infer larger discrepancies with respect to a full account of possible scenarios. This effect is not confirmed here. The finding helps to facilitate the handling of uncertainty in a DSS framework since the "preprocessing" approach is much easier to use. Both, the robustness as well as transparency of the coupled approach carries a large potential for enhancing the efficiency of decision making even in politically sensitive situations.

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