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In-depth analysis of accidental oil spills from tankers in the context of global spill trends from all sources

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Abstract

This study gives a global overview of accidental oil spills from all sources (≥700 t) for the period 1970–2004, followed by a detailed examination of trends in accidental tanker spills. The present analysis of the number and volume of tanker spills includes temporal and spatial spill trends, aspects of spill size distribution as well as trends of key factors (i.e., flag state, hull type, tanker age, accident cause and sensitivity of location). Results show that the total number and volume of tanker spills have significantly decreased since the 1970s, which is in contrast to increases in maritime transport of oil and to popular perceptions following recent catastrophic events. However, many spills still occur in ecologically sensitive locations because the major maritime transport routes often cross the boundaries of the Large Marine Ecosystems, but the substantially lower total spill volume is an important contribution to potentially reduce overall ecosystem impacts. In summary, the improvements achieved in the past decades have been the result of a set of initiatives and regulations implemented by governments, international organizations and the shipping industry.

Keywords: Oil spill; Tanker accident; Regional hotspot; Environmental pollution; ENSAD database

1. Introduction

The availability of liquid petroleum in the form of crude oil and its refined products is a key driver for all sorts of activities in modern society, but its widespread use also inevitably results in accidental and intentional releases. Examples of accidental oil spills involve vessels that come in distress or collide, oil well blowouts, pipeline ruptures, and explosions at storage facilities (e.g., [1,2]). Reductions in accident frequencies and extents can be achieved by strict safety standards, technical solutions and training of staff among other measures. However unfortunate circumstances and events such as the 1999 Kocaeli earthquake in Turkey [3] or hurricanes Katrina, Rita and Wilma in 2005 [4] can also trigger oil spill accidents. In contrast, operational discharges are mostly small, deliberate and “routine”, and can in the majority of cases be effectively controlled and/or avoided.

The impact of an accidental oil spill is primarily perceived as a major environmental problem, but associated socio-economic effects also play an important role. The extent of these impacts is likely to be determined by a diverse set of factors (e.g., [5–7]): (1) the amount, rate and type of oil spilled; (2) the location that comprises geographical position as well as political and legal issues; (3) the vicinity to sensitive resources; (4) the choice and effectiveness of cleanup strategies.

The Committee on Oil in the Sea of the National Research Council [7] has recently published updated estimates for average annual releases of petroleum inputs to the sea by source (Table 1). Natural seeps are purely natural phenomena that occur when crude oil seeps from the geologic strata beneath the seafloor to the overlying water column. These seeps are the highest contributors of petroleum hydrocarbons to the marine environment (Table 1). Nevertheless, ecological impacts seem to be limited because the slow but steady rate of release allows surrounding ecosystems to adapt and some organisms even incorporate petroleum carbon and other compounds in the releases [8–11]. But as a contaminant “background” it is important to determine the extent of pollution resulting from human activities.

The nature and size of releases due to petroleum extraction is highly variable, but is restricted to areas where active

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Table 1
Average annual contributions from major sources of petroleum in kilotonnes per year (kt/a) to worldwide marine waters for the years 1990–1999 [modified from 7]

Source	kt/a	%
Natural seeps	600	47
Extraction of petroleum	38	3
Transportation of petroleum		
Pipeline spills	12	1
Tank vessel spills	100	8
Others	41	3
Consumption of petroleum		
Land-based (river and runoff)	140	11
Operational discharges (vessels ≥100 GT)	270	21
Others	67	6

oil and gas exploration and development are under way. In the period 1985–2000, the number of offshore oil and gas platforms rose from a few thousand to about 8300 fixed or floating offshore platforms, following the increase in world oil production [7]. Historically, the largest accidental oil spill worldwide was a blowout at the Ixtoc-1 well that released 480 000 t of crude oil into the Gulf of Mexico over a 10-month period from June 1979 to February 1980 [1,2]. However, improved production technologies and safety training of personnel have dramatically reduced accidental spills from platforms to about 3% of petroleum inputs worldwide (Table 1).

Petroleum transportation can result in releases of dramatically varying sizes, from major spills associated with tanker accidents to relatively small operational releases that occur regularly. Although, releases from the transport of petroleum now amount to only about 12% of total inputs to the sea (Table 1), their potential ecological effects are of primary concern because of the complex interplay of factors involved. Finally, releases during the consumption of petroleum are as varied as its uses. Yet these typically small but frequent and widespread releases constitute the majority of the petroleum that enters the sea due to human activity (Table 1).

Although tanker spills only account for about 15% of the annual total amount of oil entering the sea (natural seeps excluded; see Table 1), they receive much attention for several reasons. Almost 60% of the oil consumed in the world is transported by tankers. Despite numerous efforts resulting in identifiable improvements, oil spills from tankers are still a major threat because many traffic routes cross the boundaries of the "Large Marine Ecosystems" and of marine biodiversity hotspots [12]. Very large spills are viewed as the most visible and dramatic causes of marine and coastal pollution as can be seen from their often exceptional media presence [13]. However, previous studies in many cases focused on particular aspects of oil spills such as the amount spilled and distributional trends (e.g., [14]), ecological consequences (e.g., [15,16]), economic costs of pollution (e.g., [5,17,18]), cleanup techniques (e.g., [19]) or examined specific geographical areas (e.g., [20,21]).

Therefore the objective of the present publication is twofold. First, a concise overview of trends in severe accidental oil spills from all sources over the last decades is given to put tanker spills into a broader perspective. Second, a comprehensive evaluation of tanker spills is provided on a global level, using available historical accident data. The various analyses address temporal and spatial trends, aspects of spill size distribution, and trends of key factors (i.e., flag state, hull type, tanker age, accident cause and sensitivity of location) for spill numbers and volumes.

2. Approach and methods

2.1. Information sources

Many countries maintain databases on tanker casualties and spills in their own waters that are generally freely accessible. In contrast, private databases are quite often only available on a commercial basis and/or include restrictions on disclosure. To obtain an accurate global data set, information from different sources need to be combined.

Such harmonized data on accidents pertaining the energy sector are available from the database ENSAD (Energy-Related Severe Accident Database), which was established at the Paul Scherrer Institut (PSI) in the mid-1990s, and since then it has been continuously maintained, updated and extended [1,2,22]. ENSAD also contains consolidated oil spill data from a wide variety of commercial and non-commercial information sources, with the most important listed in Table 2. However, about 80 other sources were also surveyed that contributed supplementary data or were used to achieve a high level of data consistency.

Table 2
Major information sources to ENSAD for accidental oil spills [1,2]

Acronym	Organisation
ETC	Environmental Technology Centre, Environment Canada
FACTS	Failure and Accidents Technical Information System, TNO Netherlands
MHIDAS	Major Hazard Incident Data Service, AEA Technology Inc. on behalf of the UK Health and Safety Executive
CTX	Center for Tankship Excellence
ITOPF	International Tanker Owners Pollution Federation
USCG	United States Coast Guard
NOAA	National Oceanic and Atmospheric Administration (e.g., Historical Incidents Database and Oil Spill Case Histories)
IMO	International Maritime Organisation
OECD	Organisation for Economic Co-operation and Development, Environmental Data
Sigma	Swiss Re Company
CEDRE	Centre of documentation, research and experimentation on accidental water pollution
ERC	Environmental Research Consulting (formerly the Oil Spill Intelligence Report database (OSIR), which was acquired by Cutter Publications, and then by Aspen Publishing, then by ERC)
US OTA	United States Office of Technical Assistance
Mariner Group	The Mariner Group, North Sea Mariner AS, Norway
IOPC Funds	International Oil Pollution Compensation Funds
REMPEC	Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea

2.2. Accident definition and damage thresholds

Different databases include various damage types and distinct minimum thresholds for each damage type to decide if an accident is considered or not [1,2]. Based on PSI's severe accident definition for ENSAD, an oil spill is considered severe if at least 10 000 t of hydrocarbons is released [2]. ITOPF distinguishes three spill size categories, namely <7, 7–700 and >700 t [23], ETC uses a minimum level of 1000 barrels (136 t) [24], and ERC includes spills of at least 10 000 gal (34 t) [25]. In the current study spills below 700 t were excluded because available information is incomplete and major differences in the quality of reporting among countries as well as ports and terminals occur [23,26], resulting in substantial underestimates for smaller-sized spills (particularly under 340 t) [14]. However, where appropriate additional analyses were performed for different spill size classes, i.e. "700–9999 t", "10 000–99 999 t" (lower limit corresponds to ENSAD severe accident definition) and "≥100 000 t" (extremely large spills).

2.3. Evaluation period

Although data for the time period from 1960 to 2004 were available, 1970 was selected as the starting year for analysis of oil spills because it allowed an adequate representation of historical experience. The number of energy-related accidents and the amount of large-scale maritime transport have both distinctly increased since the mid-1960s, mainly due to the larger volume of activities, although improved reporting coverage most likely also plays an important role [2]. This is also reflected by the fact that only 26 spills of at least 700 t were recorded in the 1960s with only 4 from 1960 to 1964. In contrast, the corresponding numbers of spills for the following three decades ranged between 197 and 283.

2.4. Oil spills from all sources

The evaluation of onshore and offshore accidental spills from all sources was limited to the number and volume of spills, contributions from different spill size classes, shares of onshore and offshore spills, and temporal trends.

2.5. Tanker spills

In this study vessels (generally tankers, barges or combined carriers) transporting crude oil or any type of petroleum products at sea or in rivers were considered. Only accidental spills were taken into account, whereas spills from acts of war and operational spillages allowed by international or national regulations (such as MARPOL discharges from tankers) were excluded.

Analyses of tanker spills can be assigned to four topical areas:

1. Temporal trends in annual number and volume of spills.
2. Distribution of spill volume, i.e. contribution of larger spills to total volume and vice versa.
3. Geographic distribution of spills and identification of regional hotspots.
4. Trends in spill numbers and volumes of key factors (i.e., flag state, hull type, tanker age, accident cause and sensitivity of location).

Oil tankers are the responsibility of the state in which they are registered, i.e. the flag state. For example the tanker Prestige, which spilled 63 000 t when it sank off the Galician coast of Spain in November 2002, was owned by Greek company Mare Shipping, operated by Swiss-based Crown Resources and registered in the Bahamas. A ship owner can choose its national register or any other existing register. A so-called flag of convenience ship is one that flies the flag of a country other than the country of ownership. Such a flag of convenience (FOC) can be attractive to a shipping company because several countries offer cheap registration fees, low or no taxes and freedom to employ cheap labor. Among the top five countries by flag registration in terms of tonnage (dwt, deadweight tonnes) of their oil tanker merchant fleets [27] are Panama, Liberia and the Bahamas that are designated as FOCs by the International Transport Workers' Federation (ITF) [28].

The following categories of tankers can be distinguished according to hull type. In Pre-MARPOL single hull tankers oil in the cargo tanks is separated from the seawater only by a bottom and a side plate, and they have no segregated ballast tanks in protective locations (SBT/PL). These are the oldest and most vulnerable tankers that were generally built before 1982. The major difference of MARPOL single hull tankers is that they are equipped with SBT/PL. They were mainly built between 1982 and 1996. According to a recent revision of the global timetable for the phase-out of single hull oil tankers by the International Maritime Organization (IMO) the final date for Pre-MARPOL tankers is brought forward to 2005 and for MARPOL tankers to 2010 [29]. In 1992, the MARPOL Convention was amended to make the double hull design compulsory for all new tankers (ships ordered after 6 July 1993) of 5000 dwt or more that are conducting international voyages [30]. The double hull construction incorporates both double bottoms and double sides, which means that the cargo tanks are surrounded with a second internal plate. Alternative design solutions accepted by IMO incorporate the "mid-deck" concept and the Coulombi Egg [30,31]. At the end of 2004, some 65% by tonnage, and 56% by number, of existing tankers above 5000 dwt were double hulled [32].

According to UNCTAD statistics, the average age of the world tanker fleet has decreased from 13.9 years in 2000 to 10.3 years in 2004 [27,33]. Similarly, the share of tanker tonnage aged 15 years and over decreased from 47.8% to 27.4% in the same time period.

2.6. Statistical analyses

Number and volume of oil spills from all sources were examined for differences among decades using one-way analysis of variance (ANOVA), which allows to test hypotheses about differences between two or more means (i.e. groups of samples) by comparing variances. The key statistic in ANOVA is the F-test of difference of group means that is calculated as the ratio of two estimates of variance, i.e. the between group variation divided by the within group variation. If the calculated F-value exceeds the theoretical value of the F-distribution at a chosen level of significance (α), then one can reject the null hypothesis (H0) and conclude that variances are significantly different. However most statistical packages return a p-value, which is a measure for the evidence against H0; thus the decision rule becomes "reject H0 if p-value is less than α". Subsequently a multiple comparison test such as Tukey's HSD (Honest Significant Difference) test can be used to determine between which group means significant differences exist. Data were log-transformed prior to ANOVA to improve normality and homogeneity of variances [34].

Temporal trend analyses for spills from all sources and tanker spills alone were calculated using Kendall's tau (τ) because it has some advantages over the Spearman coefficient R, particularly when data are tied. Additionally, when data are limited to only a few discrete values, Kendall's τ is also considered a more suitable statistic [35]. Results of Kendall's τ are reported in the following form: n = number of observations (years) in the time series, τ = Kendall's tau correlation coefficient and $p = p$-value.

Results of ANOVA and Kendall's tau were considered statistically significant when the probability level (p-value) was smaller than the chosen significance level of $\alpha = 0.05$. Non-significant results with a $p > 0.05$ and ≤ 0.10 were reported as "borderline cases" [36,37].

The distribution of tanker spill volumes, i.e. contribution of large spills to total volume (and vice versa), were investigated using Lorenz curves. This type of analysis was first developed by economists studying the distribution of incomes or wealth of various populations (e.g., [38,39]), but has also been applied to geographic and mineralogical data (e.g., [40,41]). Generally, a Lorenz curve compares the distribution of a specific variable with the uniform distribution that represents equality [42]. A Lorenz curve for oil spills is constructed as follows. The spill data are sorted in ascending order of their spill volume, then the cumulative fraction of the volume spilled (y-axis) is plotted as a function of the cumulative fraction of the number of spills (x-axis). The variation displayed by a Lorenz curve can be summarized using the Gini index. The value of the index ranges from 0 to 1, 0 representing perfect equality and 1 total inequality [42]. A complementary perspective on spill volumes is provided by the cumulative distribution function (CDF), which shows the proportion of spills with a volume less than or equal to a specified value V (y-axis) against the value of V (x-axis).

For analyzing spatial trends of oil tanker spills, the spill locations of tankers were geo-referenced using ArcGIS 9 software [43] to obtain worldwide distribution patterns. Exact geographic coordinates for locations of spills were not available in all cases; however, approximate locations could be derived with few exceptions. Spill positions were then assigned to a Marsden Square Chart, which divides the world into grids of 10° latitude by 10° longitude. Afterwards, spilled volumes in tonnes were totaled for each Marsden Square and displayed on the map as shades of gray for different spill size classes. Categories were defined using class breaks corresponding to Natural Breaks (also known as Optimal Breaks and Jenks' Method) [43,44]. Using this method, data are classed along the size distribution so that the variances within all classes are minimized, while the variances among classes are maximized. In this manner the data distribution is explicitly considered for determining class breaks, which is the major advantage of this method. The major disadvantage is that the concept behind the classification may not be easily understood by all map users, and the legend values for the class breaks (e.g., the data ranges) may not be intuitive.

A global analysis addressing spatial autocorrelation of spilled oil volumes in tanker accidents across all locations was performed to detect if data are clustered or randomly distributed in space. Moran's I [45] and Geary's c [46] are well known methods for testing for spatial autocorrelation. Both, Moran's I and Geary's c can be tested for significance against their theoretical distribution (e.g., [47–49]). Moran's I was used in the present study because there is some evidence that it is slightly better than Geary's c (e.g., [48,50]). The expected value of Moran's I is $-1/(N-1)$. Computing z-scores transforms the raw values to a standard normal distribution by the formula $z = (X - \mu)/\sigma$, where X is a raw value, μ the mean, and σ is the standard deviation. A z-score always reflects the number of standard deviations above or below the mean for a particular value. For example, at a significance level of $\alpha = 0.05$, a z-score would have to be less than -1.96 or greater than 1.96 to be statistically significant. Values of I that exceed $-1/(N-1)$ or z-scores >0 indicate positive spatial autocorrelation, where similar values, either high values or low values, are spatially clustered. Values of I below $-1/(N-1)$ or z-scores <0 indicate negative spatial autocorrelation, in which neighboring values are dissimilar. Additionally, Getis-Ord General G [51] was applied, which is a high/low variation tool measuring concentrations of high or low values for an entire study area. Here a positive z-score for G indicates spatial clustering of high values, and a negative z-score indicates spatial clustering of low values. Spatial statistics were computed using ArcGIS 9 software [43]. Finally, it was analyzed how many spills occurred in ecologically sensitive areas because they are located within the boundaries of the Large Marine Ecosystems (LME) of the world. These are ocean regions of 200 000 km^2 or greater with a distinct bathymetry, hydrography, productivity and trophically dependent populations [52].

A number of key factors such as flag state, hull type, tanker age, accident cause and sensitivity of location were investigated in more detail. For each factor differences among several categories were analyzed for annual spill numbers and volumes using one-way ANOVA (see above). Flag states were assigned to four groups, namely flags of convenience (FOC) [28], EU25, other OECD and non-OECD countries. Hull types considered were Pre-MARPOL single hull, MARPOL single hull, double sides only and double bottom only hull constructions, and double hull. However, only the first two categories were used in current analyses because accidents with other hull types rarely occurred. Tanker age at the time of the accident followed UNCTAD categories, i.e. 0–4, 5–9, 10–14, 15–19, and 20 and more years [27]. Accident cause was evaluated in terms of the primary event occurring at the time of the spill. Categories considered were

Collision, Explosion/Fire, Grounding, Hull/Structural Failure, and Other. Sensitivity of location was determined depending if a spill occurred within LME-boundaries or not. At last, temporal trends for each category of a factor were analyzed by means of Kendall's τ (see above).

3. Results and discussion

3.1. Oil spills from all sources

In total, 737 accidental oil spills with at least 700 t were included in the analysis for the period 1970–2004 (Fig. 1). Total numbers of spills exhibited a substantial decrease in the 1980s and 1990s compared to the 1970s. This reduction is primarily attributable to spills from 10 000 t to smaller 100 000 t, whereas spill numbers below 10 000 t varied less among decades, and extremely large spills (≥100 000 t) remained stable over the last three decades. When the data for years 2000–2004 are linearly extrapolated to the full decade, further reductions in spill numbers could be expected if the currently prevailing trend continues.

One-way ANOVAs for spill numbers were performed for the different spill size classes and total spill numbers. Significant statistical differences among decades were found for the category 10 000–99 999 t ($F = 9.75$, $p = 0.0006$), and so-called "borderline" significance was found for total spill numbers ($F = 2.47$, $p = 0.10$). Overall, results are indicative that large and very large spills were successfully reduced since the 1970s. Data from 2000 onward suggest that a similar decrease could be achieved for spills below 10 000 t.

Fig. 2 shows the volumes of accidental offshore and onshore oil spills (≥700 t) from all sources for the period 1970–2004. Decade averages of offshore spill volumes were highest in the 1970s mainly attributable to a few very large spills in the second half of this decade, followed by a significant decrease in the 1980s and 1990s. In contrast, average onshore spill volumes more than doubled in the 1990s because of four accidents of

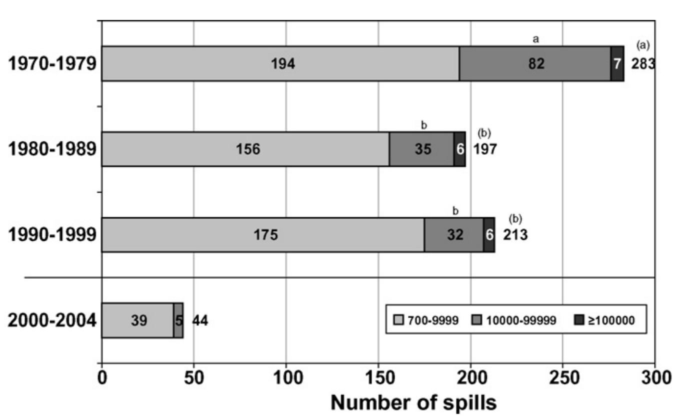

Fig. 1. Numbers of accidental oil spills (≥700 t) per decade from all sources are given according to different size classes and totals for the period 1970–2004. The years 2000–2004 are also shown to give an approximate indication of how observed trends could continue. Based on one-way ANOVA, significant differences in spill numbers among decades within a particular spill size category are indicated by different letters; parentheses denote "borderline" significance.

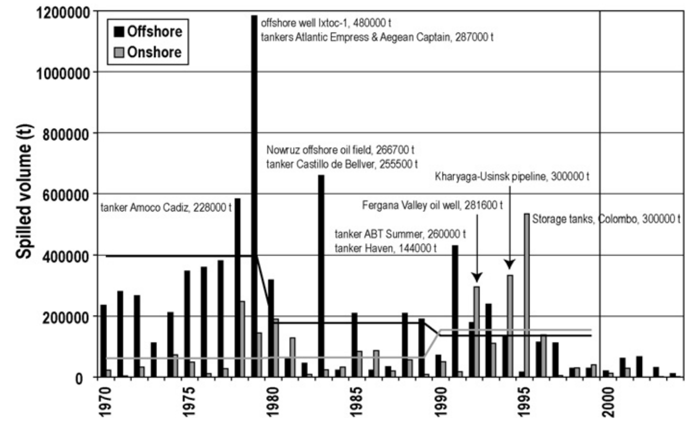

Fig. 2. Annual volumes of accidental offshore and onshore oil spills (≥700 t) from all sources for the period 1970–2004. Lines represent averages per decade. The 10 largest spills are also shown.

Table 3
Percentages of numbers and volumes of accidental oil spills (≥700 t) by source type

Decade	Pipeline	Platform/well/ rig/mobile unit	Storage tank/ refinery/other fixed facility	Tanker
Share of number of spills (%)				
1970–1979	3.5	4.3	5.3	86.9
1980–1989	6.6	3.5	10.2	79.7
1990–1999	37.6	1.4	13.6	47.4
1970–1999	15.6	3.1	9.2	72.1
Share of spilled volume (%)				
1970–1979	1.3	16.1	8.0	74.6
1980–1989	1.1	22.3	14.9	61.7
1990–1999	24.6	10.0	18.7	46.7
1970–1999	8.1	15.4	12.8	63.7

more than 100 000 t. Consequently, the values for a particular year may be strongly driven by extremely large accidents[1] such as the blow-out on the platform Ixtoc-1 (1979) or the collision of the Atlantic Empress and the Aegean Captain (1979) for offshore spills, and the leakage of the Kharyaga-Usinsk Pipeline in Russia (1994) or an oil well blow-out in Uzbekistan (1992) for onshore spills. Kendall's τ for spilled volumes exhibited a significant downward trend for offshore spills ($n = 30$, $\tau = -0.33$, $p = 0.01$), and an upward tendency for onshore spills ($n = 30$, $\tau = 0.18$, $p = 0.16$). Currently available data from 2000 onward suggest that observed trends will continue.

Corresponding results for numbers of offshore and onshore spills are not shown, but they exhibited similar trends as reflected by Kendall's τ with a significant decrease for offshore spills ($n = 30$, $\tau = -0.37$, $p = 0.004$) and a significant increase for onshore spills ($n = 30$, $\tau = 0.49$, $p = 0.0001$).

Table 3 shows percentage contributions by spill source type for spills of at least 700 t. In the 1990s shares of cumulated spill

[1] Note that the biggest spill ever occurred during Gulf War II in 1991 when between 768 000 and 1 770 000 t spilled from oil terminals and tankers. However, spills due to acts of war were excluded from the present analysis as explained in Chapter 2.

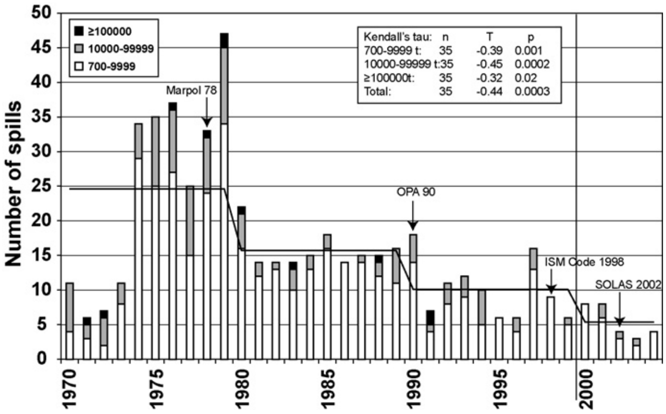

Fig. 3. Cumulated annual numbers of accidental oil tanker spills (≥700 t) according to different size classes are given for the period 1970–2004. The thick black line represents decade averages. Years of enactment of different regulation frameworks are also indicated. The inset table summarizes results of Kendall's τ, where n = number of years in the time series, τ = Kendall's tau correlation coefficient and p = p-value.

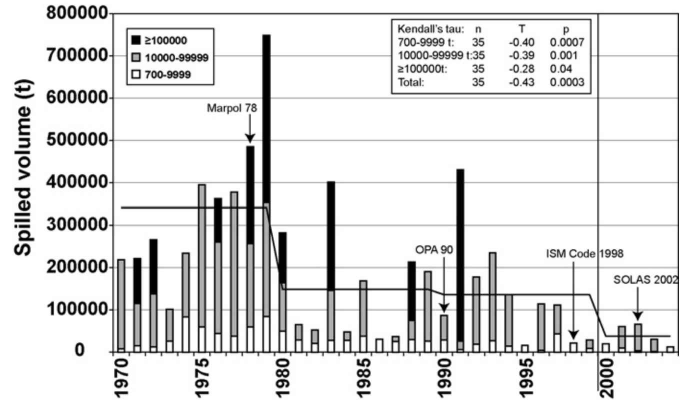

Fig. 4. Cumulated annual volumes of accidental oil tanker spills (≥700 t) according to different size classes are given for the period 1970–2004. The thick black line represents decade averages. Years of enactment of different regulation frameworks are also indicated. The inset table summarizes results of Kendall's τ, where n = number of years in the time series, τ = Kendall's tau correlation coefficient and p = p-value.

numbers and volumes for the categories "Tanker" and "Platform/Well/Rig/Mobile Unit" were clearly below totals for the three decades, reflecting a substantial decrease over time. A reversed trend was found for the two other categories; particularly shares for "Pipeline" more than doubled in terms of spill numbers and even tripled in terms of spilled volume.

3.2. Oil spills from tankers

3.2.1. Temporal trends in spill numbers and volumes

Figs. 3 and 4 show the annual numbers and volumes of accidental spills (≥700 t) from tankers according to the different spill size classes for the period 1970–2004. Out of 531 spills only 24.3% resulted in a release of at least 10 000 t, but they accounted for 84.9% of the total spilled volume. Numbers and volumes of spills significantly decreased over the period of observation, both for the different spill size classes and cumulated values, respectively. Respective test statistics of Kendall's τ are given in Figs. 3 and 4.

Average total numbers of spills declined about 36% from the 1970s to the 1980s as well as from the 1980s to the 1990s. For average spilled volumes the reduction was most substantial from the 1970s to the 1980s (about 56%), but only about 9% from the 1980s to the 1990s. Finally, spills with a volume greater than 100 000 t are relatively scarce events, totaling 11 over the whole period of observation (Table 4). However, since the two accidents of the tankers Haven (144 000 t) and ABT Summer (260 000 t) in 1991 no other of this size category has occurred.

The declining trends in numbers of tanker spills and associated volumes observed since the 1970 are contrary to popular

Table 4
Accidental spills from oil tankers resulting in releases of at least 100 000 t (1970–2004)

Year	Ship name	Location	Spill volume (t)	Cause	Flag state	Ship age	Hull type
1979	Atlantic Empress & Aegean Captain[a]	NE of Trinidad and Tobago	287000	Collision	Greece + Liberia	5	Pre-Marpol Single hull
1991	ABT Summer	Off coast Angola	260000	Explosion/Fire	Liberia	17	Pre-Marpol Single hull
1983	Castillo de Bellver	Atlantic, off Saldanha Bay, Cape Town, South Africa	255500	Explosion/Fire	Spain	5	Pre-Marpol Single hull
1978	Amoco Cadiz	Portsall, France	228000	Grounding	Liberia	4	Pre-Marpol Single hull
1991	Haven	Off Genoa, Italy	144000	Explosion/Fire	Cyprus	18	Pre-Marpol Single hull
1988	Odyssey	Off Nova Scotia, Canada	137600	Explosion/Fire	Liberia	17	Pre-Marpol Single hull
1972	Sea Star	Gulf of Oman	127800	Collision	South Korea	4	Pre-Marpol Single hull
1980	Irenes Serenade[b]	Pylos, Navarino Bay, Greece	118000	Explosion/Fire	Greece	15	Pre-Marpol Single hull
1979	Independenta	Bosporus, Hydarpasa Port, Turkey	109000	Collision	Romania	1	Pre-Marpol Single hull
1971	Texaco Denmark	North Sea off Belgium	106300	Collision	Denmark	1	Pre-Marpol Single hull
1976	Urquiola	La Coruna, Spain	102000	Grounding	Spain	3	Pre-Marpol Single hull

Note: In the 1960s only one accident with more than 100 000 t occurred. In 1967 the Torrey Canyon ran aground near Lands End (Cornwall) and spilled 119 000 t.

[a] This accident is reported as one spill by ITOPF, whereas ETC divides it into three spills: about 138 000 t from Atlantic Empress and 14 000 t from Aegean Captain NE of Trinidad &Tobago on 19 July, and 135 000 t from Atlantic Empress E of Barbados on 2 August, after she was towed out to sea, suffered more explosions and sank.

[b] Reported spill volume ranges from 82 000 t (Intertanko) through 100 000 t (ITOPF) up to 118 000 t (ETC, ERC, Mariner Group).

perceptions shortly after catastrophic events, and to the continuous increase in worldwide seaborne oil transport by tankers particularly since the mid-1980s [53]. However, this inverse relationship can be explained by the enactment of international laws and conventions (see Figs. 3 and 4) in response to the few very large tanker spills that predominantly happened in the 1970s and to a lesser extent in the first half of the 1980s. The effects of these actions are reflected in the observed reductions of decade averages because they were implemented at the end or beginning of a decade. The MARPOL 1978 Convention deals with the prevention of pollution to the marine environment by ships from operational or accidental causes [31,54]. The Oil Pollution Act 1990 (OPA 90) was established in the USA primarily in response to the 1989 Exxon Valdez spill in Prince William Sound (Alaska). Its enactment placed increased liability on responsible parties, and other regulations required the phase-out of older vessels and the implementation of new technology and safety procedures [7]. In 1998, the International Management Code for the Safety of Ships and for Pollution Prevention (ISM Code) was implemented, which was formulated in response to a number of high profile shipping accidents during the late 1980s and early 1990s. The ISM Code is a brief set of guidelines describing what actions ship owners should undertake in order to implement a safety management system both onboard their ships and in their organizations ashore [55]. Finally, a revised SOLAS Chapter V (Safety of Navigation) was put into force in July 2002 [56]. This regulation brought in a new mandatory requirement for voyage data recorders (VDRs) to assist in accident investigations, and automatic identification systems (AIS), capable of providing information about the ship to other ships and to coastal authorities automatically.

3.2.2. Distribution of spill volumes

Lorenz curves for the cumulative proportion of spill volume of accidental oil spills (≥700 t) for the periods 1970–1999[2] and 2000–2004 show substantial heterogeneity in spill volume/event rates (Fig. 5), which is quantified by the corresponding Gini indices of 0.75 and 0.72, respectively. These measures can be used to characterize the relative contribution of extreme events towards total spill volume. The current results demonstrate that few large spills account for the majority of total spill volume, whereas most spills are relatively small. For example, 50% (the median) of spills were less or equal to 2500 t amounting to only about 5% of total spill volume, while the largest 10% of spills (≥32 000 t) accounted for 63% of total spill volume in the years 1970–1999. For the years 2000–2004, half of all spills were less or equal to 1540 t (8% of total spill volume), and the largest 10% (≥11 520 t) contributed 69% of total spill volume.

Distributions of total spill volume and relative shares of large spills for the two periods examined are rather similar. However, when comparing the cumulative distribution function (CDF) for the two periods (Fig. 6), it becomes apparent that large differences exist in terms of absolute values. This applies to maximum spill size (287 000 t in 1970–1999 versus 63 000 t in 2000–2004) as well as spill size at the median and 90th percentile.

Overall, the distribution of spill volumes provides important information of the extent to which large and extremely large spills disproportionately contribute to total spill volume. Such knowledge can be helpful, e.g. when evaluating the relative value of preventive efforts on extreme spill events. In contrast, small spills are generally of less concern because they are more likely to be contained on site and they have a lower potential to lead to significant adverse environmental impacts.

3.2.3. Geographic distribution of spills and identification of regional hotspots

Geographic locations were available for 508 out of a total of 531 tanker accidents in the years 1970–2004 that each resulted

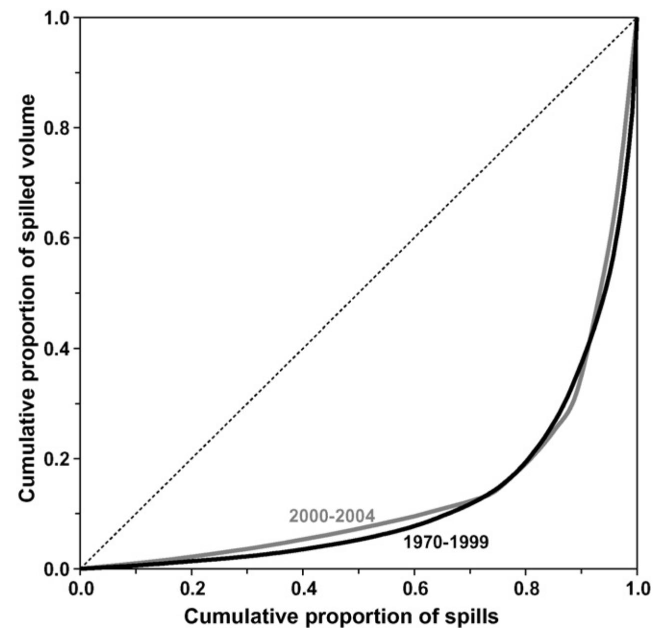

Fig. 5. Lorenz curves of accidental oil spills (≥700 t) for the years 1970–1999 and 2000–2004. The dashed diagonal represents the perfect equality line, which is a linear relationship that plots a distribution where each element has an equal value in its shares of *X* and *Y*.

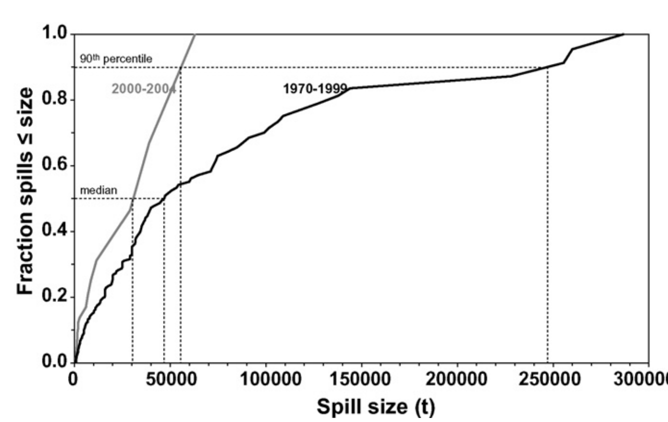

Fig. 6. Cumulative distribution functions of accidental oil spills (≥700 t) for the years 1970–1999 and 2000–2004. Median and 90th percentile are indicated by dashed lines.

[2] Separate Lorenz curves and associated Gini indices for decades (1970–1979, etc.) were rather similar, thus only cumulated results for 1970–1999 are shown.

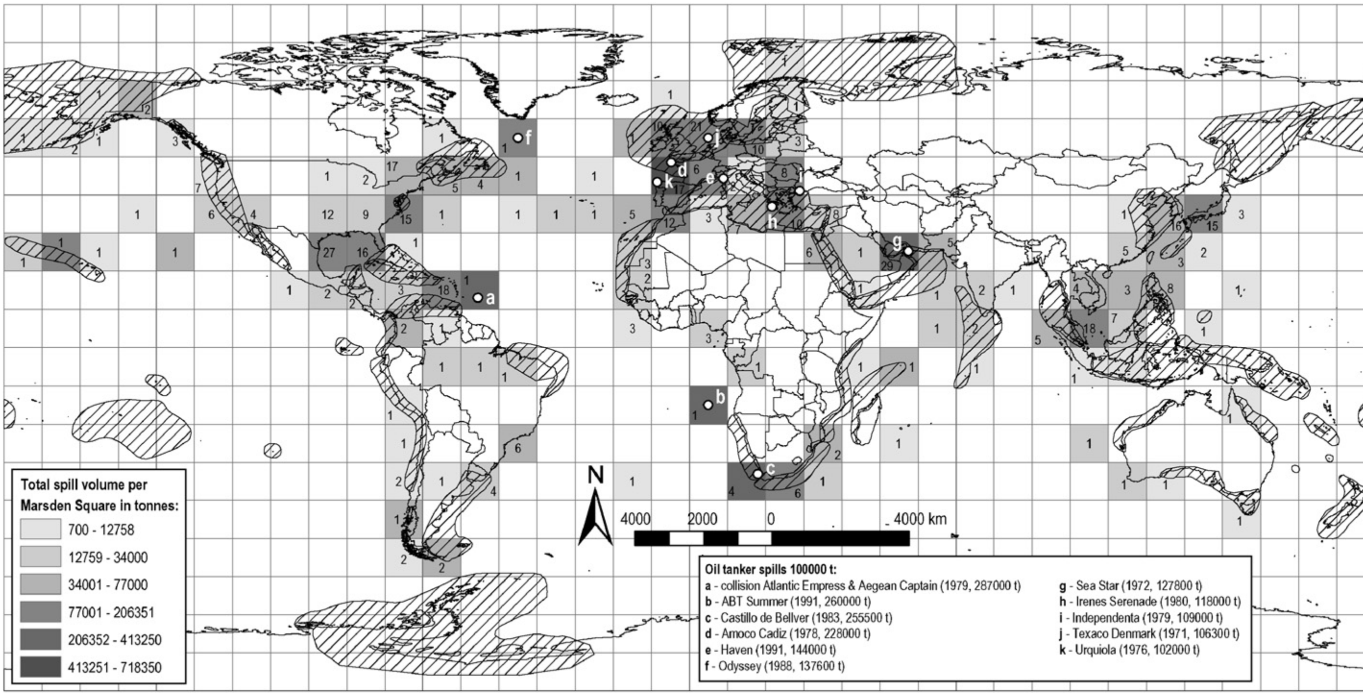

Fig. 7. The worldwide distribution of oil tankers involved in spills of at least 700 t for the period 1970–2004 is shown on the map. Individual Marsden Squares (10° latitude by 10° longitude) are shaded in different intensities of gray according to the total spilled volume in tonnes, with class breaks corresponding to Natural Breaks (see Chapter 2 for details). Small numbers within each Marsden Square represent the number of spills that occurred within that particular grid cell. Additionally, spills resulting in releases of at least 100 000 t are labeled (a–k) and briefly described (for details see Table 4).

in a spill of at least 700 t. These accidents were plotted on a Marsden Square Chart of the world. The map in Fig. 7 shows high spill volumes for several areas:

- the Northern European Atlantic, particularly the coast of Galicia in Spain and the English Channel, and to a lesser extent for the North Sea;
- the Eastern Mediterranean;
- the Gulf of Mexico, the Caribbean and parts of the Southern Atlantic down to Venezuela and Brazil;
- around the Southern tip of Africa where the Atlantic and Pacific Ocean come together;
- the Persian Gulf including parts of the Arabian Sea;
- the Strait of Malacca, the Gulf of Thailand and the South China Sea.

Extremely large spills with a volume of at least 100 000 t all occurred in these regions, except the Odyssey spill in 1988 that took place off Nova Scotia (Canada). These regions also belonged to the most affected ones in terms of numbers of spills.

Moran's I ($I = 0.02$, z-score = 13.8, $p = 0.01$) indicated that spill locations showed a clustered pattern. Additionally, Getis-Ord General G ($G = 0.02$, z-score = 13.5, $p = 0.01$) revealed a clustering of high values. These findings confirm the previous description of regional spill hotspots.

ArcGIS was used to identify those spills that occurred in ecologically sensitive areas because they are located within the boundaries of the Large Marine Ecosystems (LME) of the world. In total, 223 (44%) out of 508 spills occurred within LME-boundaries and another 41 (6%) no more than 100 km away; corresponding to 49% and 54% of total spill volume, respectively (Fig. 7).

LMEs also encompass coastal areas from river basins and estuaries to the seaward boundaries, which indirectly supports findings from other studies showing that near-shore spills can often have more severe consequences than offshore spills [55]. Additionally, the numbers and volumes of spills are strongly correlated with maritime routes of worldwide oil transport [7] that often pass through LMEs [52]. As a consequence, coastal areas are particularly susceptible to accidental spills due to denser traffic and shallow water increasing the risk of collision and grounding.

However, consequences of a spill are not a simple function of distance to the coast because a complex array of interrelated factors has to be taken into consideration. This includes local conditions (e.g., weather conditions, water currents and depths, and tidal range), vulnerability of different shoreline types [57] as well as ecosystem differences in persistence and resilience following disturbance, including seasonal changes in sensitivities. Finally, several studies [15,19] have shown that accidents occurring in autumn and winter often coincided with storms or bad weather complicating or disabling oil collection and prompt spill response, and thus enhancing the potential risk of more severe consequences.

3.2.4. Relationship between key factors and spill numbers and volumes

In Table 5, results of ANOVAs including Tukey's HSD tests and Kendall's τ are summarized for changes in spill numbers

Table 5
Summary of changes in annual spill numbers and volumes of key factors of accidental tanker spills (≥700 t) in the period 1970–2004 ($n = 35$)

	Anova				Kendall's τ			
	Number of spills		Spilled volume		Number of spills		Spilled volume	
	F	p	F	p	τ	p	τ	p
Flag state[a]	12.66	**<0.0001**	9.28	**<0.0001**				
EU25	a		a		−0.35	**0.01**	−0.43	**0.0004**
Other OECD	a		a		−0.19	0.16	−0.27	**0.04**
FOC	b		b		−0.05	0.72	−0.20	(**0.09**)
Other non-OECD	a		a		0.31	**0.02**	0.20	(**0.10**)
Hull type[a]	40.58	**<0.0001**	33.97	**<0.0001**				
Pre-MARPOL single hull	a		a		−0.60	**0.000002**	−0.44	**0.0002**
MARPOL single hull	b		b		0.50	**0.0002**	0.48	**0.0002**
Tanker age (years)	1.25	0.29	1.43	0.23				
0–4	a		a		−0.25	(**0.06**)	−0.29	**0.02**
5–9	a		a		−0.28	**0.04**	−0.33	**0.008**
10–14	a		a		−0.04	0.75	−0.08	0.52
15–19	a		a		−0.22	(**0.09**)	−0.17	0.16
≥20	a		a		0.22	(**0.11**)	0.24	**0.05**
Accident cause	25.71	**<0.0001**	15.66	**<0.0001**				
Collision	a		a		−0.08	0.53	−0.36	**0.003**
Explosion/fire	b		a,b		−0.37	**0.04**	−0.25	**0.04**
Grounding	a		a		−0.18	0.16	−0.28	**0.02**
Hull/structural failure	c		b		−0.26	**0.05**	−0.24	**0.05**
Other	c		c		0.07	0.65	−0.02	0.91
LME	2.51	0.12	0.77	0.38				
Within LME	a		a		−0.38	**0.002**	−0.47	**0.00007**
Outside LME	a		a		−0.44	**0.0003**	−0.31	**0.008**

For each factor differences between categories were analyzed by ANOVA; different letters indicating statistical significance. Temporal trends within individual categories were assessed by Kendall's τ statistic. Significant p-values are given in bold; parentheses denote "borderline significance". FOC: flag of convenience; LME: large marine ecosystems; F: F-value; τ: Kendall's tau correlation coefficient; p: p-value.
[a] Factor categories.

and volumes of key factors of tanker spills (≥700 t) in the period 1970–2004.

3.2.4.1. Flag state. The analysis of flag state affiliations indicated significant differences among country groups, with spill numbers and volumes in FOC countries being significantly higher compared to other country groups. Although not all temporal trend analyses for individual country groups were statistically significant, a trend of decreasing spill numbers and volumes was found for EU25, other OECD and FOC countries, whereas other non-OECD countries exhibited an opposite pattern. However, annual averages in the last 10 years (1995–2004) still show large differences among country groups. While average spill volume for EU25 and other OECD countries decreased to roughly 1000 t, FOC countries remained at much higher levels (around 30 000 t). Other non-OECD countries (around 10 000 t) were still clearly below FOC countries, although increasing over time.

In a recent analysis, Tolsdorf and Losen [58] similarly reported that after 1979 the accident risks of tankers under FOCs have steadily converged to the level of traditional national registers. The authors argue that operational factors as well as changes in business conditions and liabilities may have triggered this development.

An alternative approach to compare flag states has been proposed by Alderton and Winchester [59], who evaluated how the categorization of flag states is affected by globalization. Based on the so-called "flag state conformance index" (FLASCI) created by the authors, 37 countries were assigned to 5 groups from "high" to "low", according to the extent and effectiveness of their regulatory regimes. Using this method, traditional maritime countries (e.g. Norway, United Kingdom) and semi-autonomous second registers (e.g. Hong Kong, Bermuda, Singapore) are rated "high" and "medium-high", more established open registers (e.g., Liberia, Panama, Cyprus and Malta) are in the category "medium", whereas the "low category consists of new entrants to the open register market (e.g. Saint Vincent and the Grenadines, Belize and Cambodia).

3.2.4.2. Hull type. Pre-MARPOL single hull tankers showed to be significantly more accident-prone than MARPOL single hull tankers, accounting for the majority of total oil spilled. Over the period of observation, tankers with Pre-MARPOL single hull construction showed a decrease in spill numbers and volumes, contrary to tankers with MARPOL single hull construction.

Spills with volumes over 100 000 t only occurred with Pre-MARPOL single hull tankers, whereas maximum spills for

MARPOL single hull (1996, Sea Empress, 74 700 t), double bottom only (1992, Aegean Sea, 70 400 t) and double sides only (1993, Frontier Express, 8320 t) were substantially lower. Finally, accidents with double hull tankers have caused no spills larger than 5000 t (2001, Baltic Carrier, 2700 t) to date.

Oil pollution of the seas was already recognized as a problem in the first half of the 20th century resulting in the adoption of the International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL 1954) that was put into force in 1958 [60]. However, accidental pollution control remained a minor issue until the Torrey Canyon spill in 1967 with a volume of 119 000 that was the biggest up to that time. As a consequence efforts were not only undertaken to define measures to prevent oil pollution from ships, but also to eliminate deficiencies in the existing system for providing compensation following accidents at sea. The outcome of this process was the MARPOL Convention 73/78 [31]. The change in the composition of the world tanker fleet from a dominance of more vulnerable single hull construction towards safer double hull construction was primarily enforced by amending MARPOL 73/78 with Regulation 13F (double hull requirements for tankers ordered after 6 July 1993) [30] and Regulation 13G (accelerated phase-out of Pre-MARPOL and MARPOL single hull tankers by 2005 and 2010, respectively) [29] as a reaction to the Prestige spill in 2002.

3.2.4.3. Tanker age. Spill numbers and volumes of different tanker age categories were not significantly different, but results for individual categories were indicative of a reduction in the contribution of tankers less than 10 years old over the last three decades, whereas for tankers of 20 and more years an increase was observed.

These opposing trends in different tanker age classes are also related to the previously described shift in predominant hull types. Larger spills in recent years mostly concerned Pre-MARPOL single hull tankers built in the 1970s such as the Erika in 1999 (20 000 t spilled, built in 1975), the Prestige in 2002 (63 000 t, 1976) and the Tasman Spirit in 2003 (29 000 t, 1979) or MARPOL single hull tankers built in the early 1980s such as the Petrolimex 01 in 2001 (39 000 t, 1983). However, with the accelerated final phase-out of ships with single hull constructions (Pre-MARPOL in 2005 and MARPOL not later than 2010) [61], the composition and average age of the world tanker fleet is changing. At the end of 2004, double hull tankers above 5000 dwt made up some 65% by tonnage of the world tanker fleet [27]. At the same time 51% of double hull tankers were less than 5-year old, and another 29% below 10 years [62], contributing to a reduction in the average age of the world tanker fleet from 13.9 years in 2000 to 10.3 years in 2004 [27,33].

3.2.4.4. Accident cause. Tanker spills can be caused by a combination of events coming together to produce the final outcome. The analysis presented here is based on the primary event at the time of the spill. Significant differences among different spill causes were found, both for spill numbers and volumes. The dominant causes were attributable to the categories Collision, Explosion/Fire and Grounding that cumulatively accounted for more than 80% of spill causes.

3.2.4.5. Sensitivity of location. Spill numbers and volumes within LME-boundaries and outside were not significantly different. Although absolute values for both categories decreased over the period of observation, their relative shares did not. However, the reductions from an average of about 160 000 t per year in the 1970s to 80 000 t and 60 000 t in the following decades provide an essential relief of ecosystem stress within LMEs. Data for 2000–2004 (about 5000 t) indicate that a further substantial reduction could be achieved. This improvement is of particular importance because within their waters LMEs not only produce 95% of the world's annual marine fishery biomass yields, but they are also zones with some of the most important and fragile coral reef ecosystems and marine biodiversity hotspots worldwide [12,63].

4. Conclusions

As a result of recent efforts the basis for comparative analyses of accidental oil spill risks has been significantly improved. This applies in particular to the completeness of historical records, quality and consistency of the information, and scope of analyses.

131 offshore and 43 onshore severe (≥10 000) oil spills from all sources occurred between 1970 and 2004. In this list the largest accidental tanker spill according to volume ranks only fourth. Concerning cumulated spill numbers and volumes, percent shares for tankers in the 1990s were clearly below totals for the total period 1970–1999, whereas it was the opposite for pipelines.

Contrary to increases in oil movement and to popular perceptions after recent catastrophic events, the numbers and volumes of tanker spills have substantially decreased since the 1970s. Concomitantly, maximum spill size as well as 90th percentile and median spill size also declined, although the relative contribution of the largest 10% of total spill volume remained at about two thirds. This development is also reflected in trends of several key factors, e.g. accident risks of tankers under FOCs approach those of traditional maritime countries, conversion of the world tanker fleet from vulnerable single hull to safer double hull constructions, and accordingly a decrease in the average age of the world tanker fleet.

However, many spills still occur within the boundaries of the Large Marine Ecosystems because the major maritime transport routes pass through them. But the substantial decrease in total spill volume, also in these ecologically sensitive areas, could potentially reduce overall ecological and socio-economic impacts, although each spill involves a unique set of circumstances.

The achieved improvements are the result of a continuous process involving the enactment of numerous regulations at national and international levels. In addition to measures onboard, along transport routes and ashore for increased safety and spill prevention, future efforts need to be complemented by the deployment of efficient contingency programs, particularly in sensitive and spill hotspot regions.

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References

[1] P. Burgherr, S. Hirschberg, A. Hunt, R.A. Ortiz, Severe accidents in the energy sector, in: R. Friedrich (Ed.), New Elements for the Assessment of External Costs from Energy Technologies (NewExt). Final Report to the European Commission, DG Research, Technological Development and Demonstration (RTD), Brussels 2004.
[2] S. Hirschberg, G. Spiekerman, R. Dones, Severe accidents in the energy sector, 1st ed., PSI Report No. 98-16, Paul Scherrer Institut, Villigen PSI, 1998.
[3] A.M. Cruz, L.J. Steinberg, Industry preparedness for earthquakes and earthquake-triggered hazmat accidents in the 1999 Kocaeli earthquake, Earthquake Spectra 21 (2005) 285–303.
[4] Associated Press, Hurricanes cause 8 million gallons of oil to be spilled in state (14 October 2005), Associated Press, Baton Rouge, 2005.
[5] D.S. Etkin, Estimating cleanup costs for oil spills, in: Proceedings of the 1999 International Oil Spill Conference, API Publication No. 4686, American Petroleum Institute, Washington, D.C., 1999.
[6] D.F. McCay, J.J. Rowe, N. Whittier, S. Sankaranarayanan, D.S. Etkin, Estimation of potential impacts and natural resource damages of oil, J. Hazard. Mater. 107 (2004) 11–25.
[7] National Research Council (NRC), Oil in the sea: inputs, fates, and effects, National Academy of Sciences, Washington, DC, 2003.
[8] P.A. Montagna, J.E. Bauer, M.C. Prieto, D.H. Hardin, R.B. Spies, Benthic metabolism in a natural coastal petroleum seep, Marine Ecol. Prog. Ser. 34 (1986) 31–40.
[9] P.A. Montagna, J.E. Bauer, J. Toal, D.H. Hardin, R.B. Spies, Vertical distribution of meiofauna in the sediment of a natural hydrocarbon seep, J. Marine Res. 47 (1989) 657–680.
[10] R.B. Spies, P.H. Davies, D. Stuermer, Ecology of a petroleum seep off the California coast, in: R. Geyer (Ed.), Marine Environmental Pollution, Elsevier, Amsterdam, 1980, pp. 229–263.
[11] R.B. Spies, D.J. DesMarais, Natural isotope study of trophic enrichment of marine benthic communities by petroleum seepage, Marine Biol. 73 (1983) 67–71.
[12] C.M. Roberts, C.J. McClean, J.E.N. Veron, J.P. Hawkins, G.R. Allen, D.E. McAllister, C.G. Mittermeier, F.W. Schueler, M. Spalding, F. Wells, C. Vynne, T.B. Werner, Marine biodiversity hotspots and conservation priorities for tropical reefs, Science 295 (2002) 1280–1284.
[13] A.G. Anderson, The media politics of oil spills, Spill Sci. Technol. Bull. 7 (2002) 7–15.
[14] D.S. Etkin, Analysis of oil spill trends in the United States and worldwide, in: 2001 International Oil Spill Conference, API Publication, American Petroleum Institute, Washington D.C., 2001.
[15] T. Höfer, Tanker safety and coastal environment: Prestige, Erika, and what else? Environ. Sci. Pollut. Res. 10 (2003) 1–5.
[16] C.H. Peterson, S.D. Rice, J.W. Short, D. Esler, J.L. Bodkin, B.E. Ballachey, D.B. Irons, Long-term ecosystem response to the Exxon Valdez oil spill, Science 302 (2003) 2082–2086.
[17] K.J. Purnell, Comparative costs of low technology shoreline cleaning methods, in: Proceedings of the 1999 International Oil Spill Conference, API Publication No. 4686, American Petroleum Institute, Washington D.C., 1999.
[18] I.C. White, F.C. Molloy, Factors that determine the cost of oil spills, in: Proceedings of the 2003 International Oil Spill Conference, American Petroleum Institute Publication No. 14730 A (CD-ROM), Washington D.C., 2003.
[19] J. Whitfield, How to clean a beach, Nature 422 (2003) 464–466.
[20] HELCOM, Activities 2004–overview. Baltic Sea Environment Proceedings No. 102, 2005. Available online at: http://www.helcom.fi/stc/files/Publications/Proceedings/bsepl02.pdf (consulted December 2005).
[21] D.R. Vieites, S. Nieto-Roman, A. Palanca, X. Ferrer, M. Vences, European Atlantic: the hottest oil spill hotspot worldwide, Naturwissenschaften 91 (2004) 535–538.
[22] S. Hirschberg, P. Burgherr, G. Spiekerman, R. Dones, Severe accidents in the energy sector: comparative perspective, J. Hazard. Mater. 111 (2001) 57–65.
[23] ITOPF, Oil spill tanker statistics: 2004, 2005. Available online at: http://www.itopf.com/stats04.pdf (consulted December 2005).
[24] ETC, Environmental Technology Centre—Environment Canada, 2001. Available online at: http://www.etc-cte.ec.gc.ca (consulted December 2005).
[25] D.S. Etkin, Historical overview of oil spills from all sources (1960–1998), in: 1999 International Oil Spill Conference, API Publication, American Petroleum Institute, Washington D.C., 1999.
[26] K. Huijer, Trends in oil spills from tanker ships 1995–2004, in: Proceedings of the 28th Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Calgary (Alberta), Canada, 2005.
[27] UNCTAD, Review of maritime transport 2005. United Nations Conference on Trade and Development, Geneva, 2005. Available online at: at: http://www.unctad.org/en/docs/rmt2005_en.pdf (consulted January 2006).
[28] ITF, Campaign against flags of convenience and substandard shipping. Annual report 2004. International Transport Workers' Federation (ITF), London, UK, 2005.
[29] IMO, Regulation 13G of Annex I of MARPOL 73/78, International Maritime Organization, London, UK, 2003.
[30] IMO, Regulation 13F of Annex I of MARPOL 73/78, International Maritime Organization, London, UK, 1992.
[31] IMO, MARPOL 73/78 (Consolidated edition, 2002), International Maritime Organization, London, UK, 2002.
[32] EMSA, EMSA works with industry on tankers solution, 2005. Available online at: http://www.emsa.eu.int/ennews20050609144408.html (consulted January 2006).
[33] UNCTAD, Review of maritime transport 2001. United Nations Conference on Trade and Development, Geneva, 2001. Available online at: http://www.unctad.org/en/docs/rmt2001-en.pdf (consulted January 2006).
[34] J.H. Zar, Biostatistical Analysis, Prentice-Hall, Upper Saddle River, New Jersey, USA, 1999.
[35] W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling, Numerical Recipes: The Art of Scientific Computing, Cambridge University Press, Cambridge, UK, 1986.
[36] W.R. Rice, Analyzing tables of statistical tests, Evolution 43 (1989) 223–225.
[37] N.G. Yoccoz, Use, overuse, and misuse of significance tests in evolutionary biology and ecology, Bull. Ecol. Soc. Am. 72 (1991) 107–111.
[38] J. Aitchison, J.A.C. Brown, The Lognormal Distribution with Special Reference to Its Uses in Economics, Cambridge University Press, Cambridge, UK, 1969.
[39] W.J. Baumol, Economics Principles and Policy, 2nd ed., Harcourt Brace Jovanovich, Inc., New York, USA, 1982.
[40] L.J. King, Statistical Analysis in Geography, Prentice-Hall, Englewood Cliffs, New Jersey, USA, 1969.
[41] G.S. Koch, R.F. Link, Statistical Analysis of Geological Data, Dover Publications, Inc., New York, USA, 1971.
[42] W. Lee, Characterizing exposure-disease association in human populations using the Lorenz Curve and Gini Index, Stat. Med. 16 (1997) 729–739.
[43] ESRI, ArcGIS 9, Environmental Systems Research Institute Inc. (ESRI), Redlands, California, 2005.
[44] G.F. Jenks, The data model concept in statistical mapping, Int. Yearbook Cartogr. 7 (1967) 186–190.
[45] P. Moran, The interpretation of statistical maps, J. Roy. Stat. Soc. B 10 (1948) 243–251.

[46] R.C. Geary, The contiguity ratio and statistical mapping, Incorporated Stat. 5 (1954) 115–145.
[47] A.D. Cliff, J.K. Ord, Spatial Autocorrelation, Pion, London, 1973.
[48] A.D. Cliff, J.K. Ord, Spatial Process: Models and Applications, Pion, London, 1981.
[49] L. Legendre, P. Legendre, Ecologie numerique. 2. La structure des données ecologiques, Masson, Paris, 1984.
[50] S.D. Walter, The analysis of regional patterns in health data. II. The power to detect environmental effects, Am. J. Epidemiol. 136 (1992) 742–759.
[51] A. Getis, J.K. Ord, The analysis of spatial association by use of distance statistics, Geograph. Anal. 24 (1992) 189–206.
[52] K. Sherman, Productivity, perturbations and options for biomass yields in large marine ecosystems, in: K. Sherman, L.M. Alexander, B.D. Gold (Eds.), Large Marine Ecosystems: Patterns, Processes and Yields, AAAS Press, Washington, DC, 1992, pp. 206–219, 242 (second printing).
[53] Fearnresearch, Fearnleys Review 2004. Fearnresearch, Oslo, Norway, 2005.
[54] IMO, Cleaner oceans: the role of the IMO in the 1990s, International Maritime Organization, London, UK, 1990.
[55] D.S. Etkin, Worldwide analysis of marine oil spill cleanup cost factors, in: Proceedings of the 23rd Arctic and Marine Oilspill Program Technical Seminar, Winchester (MS), 2000.
[56] SOLAS, International Convention for the Safety of Life at Sea (SOLAS). A revised SOLAS chapter V (Safety of Navigation), 2002. Available online at: http://www.imo.org/Conventions/contents.asp?topicid=257&docid=647#43 (consulted June 2006).
[57] C. van Bernem, T. Luebbe, Oel im Meer: Katastrophen und langfristige Belastungen, Wissenschaftliche Buchgesellschaft, Darmstadt, 1997.
[58] F. Tolsdorf, D. Losen, Umweltrisiko unter der Billigflagge? Kostenwettbewerb und Migration - Eine empirische Analyse, in: F. Lowinski, B.P. Priddat (Eds.), Risikoökonomie. Spektren des Risikos in Wirtschaft und Gesellschaft. Wittener Jahrbuch für ökonomische Literatur Band 8, Metropolis Verlag, Marburg (Germany), 2003, pp. 201–223.
[59] T. Alderton, N. Winchester, Globalisation and de-regulation in the maritime industry, Marine Policy 26 (2002) 35–43.
[60] IMO, International Convention for the prevention of pollution of the sea by oil (OILPOL), 1954 (1981 edition), International Maritime Organization, London, UK, 1981.
[61] IMO, Amendments to Annex 1 of MARPOL 73/78: revised Regulation 13G, International Maritime Organization, London, UK, 2003.
[62] American Bureau of Shipping, Det Norske Veritas, Lloyd's Register, Common structural rules for double hull oil tankers. Structural defect experience, 2005. Available online at: http://www.jtprules.com/background/Defect%20experience%20on%20DH%20oil%20tankers.pdf (consulted January 2006).
[63] G. Hempel, K. Sherman (Eds.), Large Marine Ecosystems of the World: Trends in Exploitation, Protection, and Research, Elsevier B.V., Amsterdam, 2003.